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Halogenated Solvent Cleaners

Radian Corp., Research Triangle Park, NC

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16. ABSTRACT

This document contains information on the use and control of halogenated solvents in solvent cleaning applications. Described are the types of solvent cleaners manufactured, sources of solvent emissions, methods of controlling solvent emissions, and the costs associated with installation of control devices.

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Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711
August 1989

ALTERNATIVE CONTROL TECHNOLOGY DOCUMENTS

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1.0 INTRODUCTION

This document applies to cleaning machines that use halogenated solvents. It does not pertain to machines, primarily maintenance cleaners, that use petroleum distillate type solvents (such as mineral spirits and Stoddard solvents).

The use of halogenated solvents to clean or otherwise condition the surface of metal parts, electronic components, and other nonporous substrates is well established. The five commonly used halogenated solvents (methylene chloride, trichloroethylene, perchloroethylene, trichlorotrifluoroethane, and 1,1,1-trichloroethane) possess the physical characteristics necessary to handle a variety of industrial cleaning situations. They can dissolve many common residues from manufacturing processes, have little or no flammability, and can achieve a high degree of cleanliness, even on very small or intricate parts. The popularity of halogenated solvent cleaning is evidenced by the fact that hundreds of millions of pounds of the five solvents are consumed in cleaning machines each year.

However, the Environmental Protection Agency is concerned about the widespread use of the five solvents for several reasons. First, trichlorotrifluoroethane (CFC-113) and 1,1,1-trichloroethane (TCA) have been implicated in depletion of the protective stratospheric ozone layer. Second, methylene chloride, perchloroethylene, and trichloroethylene have shown evidence of being carcinogens in animals, and likely will be classified by the Agency as possible or probable human carcinogens. Finally, trichloroethylene and some components of solvent blends are photochemically reactive and contribute to the problem of unacceptably high ground level ozone concentrations in many urban areas across the United States. For solvent cleaning operations, these concerns are significant because the vast majority of solvent cleaner consumption stems from fugitive loss of solvent into the workplace, and from there, into the atmosphere. Smaller, but still significant, amounts of the halogenated solvent consumption ends up in still bottoms or cleanout residues that must be disposed of as hazardous waste. Usually, relatively minor amounts enter industrial wastewaters from halogenated solvent cleaning operations.

The Agency has announced its intent to list methylene chloride, perchloroethylene, and trichloroethylene as hazardous air pollutants and anticipates regulating them under the Clean Air Act. The Agency also has promulgated regulations implementing the Montreal Protocol on Substances that Deplete the Ozone Layer (53 FR 30566, August 12, 1988). At present, the only affected chemical widely used in halogenated solvent cleaners is CFC-113. The regulations call for CFC-113 production cuts to 50 percent of 1986 production levels by the year 1998. However, data recently analyzed by atmospheric scientists suggest that the ozone layer is being depleted more rapidly than predictive models indicated. Therefore, the Agency anticipates revisions to the Montreal Protocol to further reduce environmental release of chemicals capable of delivering chlorine or bromine to the stratosphere and catalyzing ozone destruction. Possible revisions include total phaseout of the CFC's currently subject to the Montreal Protocol, plus addition of TCA, and possibly other chemicals, to the list of covered chemicals and restrictions on TCA production. Beyond this, the Administration of EPA has announced a commitment on the part of the United States to totally phase out by the year 2000 chemicals covered by the current Montreal Protocol.

Regarding photochemically reactive cleaning solvents (VOC), the Clean Air Act (CAA) identified December 31, 1987, as the latest date for attainment of the nation ambient air quality standard (NAAQS) for ozone. As of this writing, many areas of the country are not in attainment with the ozone NAAQS. The Agency has proposed to require States that have ozone nonattainment areas to submit revised State implementation plant (SIP's) that describe what steps will be taken to attain the standard (52 FR 45044, November 24, 1987). This likely means that States will have to place additional controls on sources of VOC, including cleaning solvents.

Another recent action is the Occupational Safety and Health Administration's (OSHA) promulgation of revised permissible exposure limits (PEL) for hundreds of chemicals, including trichloroethylene and perchloroethylene (54 FR 2329, January 19, 1989). The OSHA also is working on a separate action to revise the PEL for methylene chloride. The PEL's for trichloroethylene and perchloroethylene were revised downward significantly.

Considering the promulgated and pending actions affecting the five solvents and their widespread use in cleaning operations, the Agency saw a need to disseminate emission control information on solvent cleaners. This document is intended primarily to inform State and local air pollution control agencies and solvent cleaner operators of available techniques to reduce solvent emissions and of available alternative cleaning technologies that can often be used to completely eliminate halogenated solvent use.

2.0 SUMMARY

Halogenated solvent cleaners commonly employ one of five halogenated solvents; 1,1,1-trichloroethane (TCA), trichloroethylene (TCE), perchloroethylene (PCE), methylene chloride (MC), and trichlorotrifluoroethane (CFC-113). Sometimes blends of these solvents or blends of halogenated solvents with small amounts of nonhalogenated solvents are used. Historically, hundreds of millions of pounds of the five solvents have been consumed annually in solvent cleaners. Most of the consumed solvent ends up in the atmosphere.

Cleaning machines vary in size from small benchtop models to industrial cleaners large enough to contain an automobile and in sophistication from simple tanks containing solvent to highly automated multi-stage cleaners. Machines are categorized into three types: cold cleaners, open top vapor cleaners (OTVC's), and in-line or conveyorized cleaners. Cold cleaners make use of room temperature liquid solvent for removing soils. Although many cold cleaners do not use halogenated solvent, some that do are maintenance machines often called "carburetor cleaners." They use a solvent mixture containing MC. Open top vapor cleaners heat the solvent to boiling and create a solvent vapor zone within the machine. Parts to be cleaned are lowered into the cleaner's vapor zone. Solvent vapor condenses on cooler parts dissolving and flushing away soils. In-line cleaners are enclosed devices distinguished by a conveyor system to continuously supply a stream of parts for cleaning. Cold cleaners and OTVC are batch operated. In-line cleaners can be vapor cleaners or cold cleaners; most are vapor cleaners. Data on the number of cleaners in use are scarce. Using available industry information, it is estimated that there are around 100,000 carburetor cleaners using MC, 25,000 - 35,000 OTVC, and several thousand in-line cleaners.

Emissions from solvent cleaners originate from sources such as: diffusion or evaporation of solvent from the air/solvent vapor interface, evaporation of solvent from cleaned parts as they are withdrawn from the cleaner, equipment leaks, and solvent storage and transfer losses. The majority of solvent consumed in a cleaner is lost to the air, some is lost to disposal of cleanout waste and distillation residue, and minor amounts may end up in facility wastewater. Generally, the carburetor cleaners are small emission sources. Most employ a solvent blend that forms a water layer above the liquid solvent, thereby dramatically reducing evaporative loss. In-line cleaners and OTVC's are more significant sources. Regularly used OTVC's can emit a few tons or less of solvent per year or up to perhaps 30 or 40 tons, depending heavily on the size of the machine, the type of parts cleaned, hours of operation, design of the cleaner, control equipment employed, and the operating practices followed. In-line cleaners typically emit more solvent than OTVC's, primarily because of the high volume of parts cleaned. It is common for an in-line cleaner to emit more than 20 tons of solvent per year; some have been reported to emit over 100 tons per year.

To reduce solvent cleaner emissions, and thereby solvent consumption, it is necessary first to purchase a cleaner (or retrofit an existing cleaner) with solvent saving devices/features and second to operate and maintain the cleaner properly. Tables 2-1 through 2-3 list the hardware and operating practices that have been shown to reduce solvent consumption in OTVC's, in-line cleaners, and cold cleaners, respectively. Some control devices primarily reduce

TABLE 2-1. AVAILABLE CONTROL TECHNIQUES FOR OTVC OPERATIONS

Source of Solvent Loss	Available Control Hardware	Operating Practices
Air/Solvent Vapor Interface	• 1.0 FBR (or higher) • Freeboard refrigeration device • Reduced primary condenser temperature • Automated cover • Enclosed design • Carbon adsorber • Reduced air/solvent vapor interface area	• Place machine where there are no drafts • Close cover during idle periods
Workload	• Automated parts handling at 11 fpm or less • Carbon adsorber • Hot vapor recycle/superheated vapor system	• Rack parts so that solvent drains properly • Conduct spraying at a downward angle and within the vapor zone • Keep workload in vapor zone until condensation ceases • Allow parts to dry within machine freeboard area before removal
Fugitive	• Sump cooling system for downtime • Downtime cover • Closed piping for solvent and waste solvent transfers • Leakproof connections; proper materials of construction for machine parts and gaskets	• Routine leak inspection and maintenance • Close cover during downtime

TABLE 2-2. AVAILABLE CONTROL TECHNIQUES FOR IN-LINE OPERATIONS

Solvent Loss Mechanism	Machine Design	Operating Practices
Air/Solvent Vapor Interface[b]	• 1.0 freeboard ratio • Freeboard refrigeration device[a] • Reduced primary condenser temperature[a] • Carbon adsorber • Minimized openings (clearance between parts and edge of machine opening is less than 10 cm or 10% of the width of the opening)	
Workload	• Conveyor speed at 11 fpm or less • Carbon adsorber • Hot vapor recycle/superheated vapor system	• Rack parts so that solvent drains properly • Conduct spraying at a downward angle and within the vapor zone[a] • Keep workload in vapor zone until condensation ceases • Allow parts to dry within machine before removal
Fugitive	• Sump cooling system for downtime • Downtime cover or flaps • Closed piping for solvent and waste solvent transfers • Leakproof connections; proper materials of construction for machine parts and gaskets	• Routine leak inspection and maintenance • Cover ports during downtime

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[a] Applies to in-line vapor cleaners, but not in-line cold cleaners.

[b] Air/solvent interface for in-line cold cleaners.

TABLE 2-3. AVAILABLE CONTROL TECHNIQUES FOR COLD CLEANERS

Machine Design	Operating Practices
• Manual cover • Water cover with internal baffles • Drainage facility (internal)	• Close machine during idling and downtime • Drain cleaned parts for at least 15 seconds before removal • Conduct spraying only within the confines of the cleaner

air/solvent interface losses while others primarily reduce workload related losses. Carbon adsorbers will control both. All control hardware would not be used on one machine as redundant emission control would result. However, selected combinations of the available control hardware will produce low emission machines. Chapter 4 contains more information on control device combinations. All listed operating practices can be usefully employed on any solvent cleaner.

Many States already regulate solvent cleaners, either for VOC control or for toxic pollutant control. However, the machines controlled to present State standards may be further improved by adoption of some additional control measures described in this document. A significant fraction of existing machines likely are uncontrolled. On the other hand, several equipment manufacturers currently are selling well designed solvent cleaners using the listed controls and some have improved designs on the drawing board or in prototype stage.

On existing machines, the amount of control achieved by implementing new control measures depends on the measures chosen and the degree of control already provided on the cleaner. Relative to an uncontrolled case, installing a combination of hardware controls and implementing good operating practices can reduce emissions in excess of 70 percent. Chapter 4 describes in more detail control efficiency estimates for various scenarios. For new machines, it is difficult to pinpoint what an emission rate reflecting good control should be; it depends most heavily on the cleaner size, type of workload, and working schedule. However, in the idling mode (no parts throughput), data obtained by the Agency indicate that OTVC's with controls are able to achieve an emission rate of 0.07 lb/hr/ft^2 of air/solvent interface area or lower. Data on working mode emission rates for OTVC's and in-line cleaners show wide variation.

Costs for purchasing, installing, and operating control devices listed in the tables vary widely according to the type of controls selected and the degree of sophistication. For instance, the cost of a simple mechanical hoist operated by pushbuttons may be less than $1,000, whereas a completely automated, programmable robot elevator may cost $10,000 or more. Both devices, properly operated, will reduce workload emissions over a manually operated cleaner. The more expensive model, however, offers convenience, flexibility, and reduced labor requirements that are not possible with the less expensive model. Costs detailed in Chapter 5 represent basic equipment needed to accomplish the emission reduction objective, not equipment providing additional features unrelated to emission reduction. Overall, the cost analysis shows many instances where control can be applied cost effectively. Some control scenarios show net annualized cost savings when controls are applied to an uncontrolled machine.

Although this document focuses on controls for cleaners using one of the five common halogenated solvents or solvent blends containing them, it is possible in many instances to eliminate their use entirely. In some cases water based cleaners can replace existing solvent systems. Additionally, new solvents and blends are being introduced that do not contain any of the five halogenated solvents. Most of these new solvents are being developed to replace use of CFC-113, which is being phased out. Some of them are based on heavy hydrocarbons, and some contain different partially halogenated compounds.

Although these alternative cleaning agents exist or will be available in the future, they may bring with them a different set of disadvantages. For example, they have not yet proven to be replacements (for technical reasons) in all situations currently handled by one of the five solvents, toxicity tests have not been completed on some of the proposed substitutes, water based cleaners may be relatively high energy users and may generate large wastewater streams, and moving to a substitute cleaning agent generally means buying a new cleaning machine or making expensive modifications to existing equipment. These considerations must be taken into account in decisions on how best to reduce emission of the five halogenated solvents.

3.0 ORGANIC SOLVENT CLEANER CHARACTERISTICS AND EMISSIONS

3.1 GENERAL

Organic solvent cleaners use organic solvents, solvent blends, or their vapors to remove water-insoluble soils such as grease, oils, waxes, carbon deposits, fluxes and tars from metal, plastic, fiberglass, printed circuit boards, and other surfaces. Organic solvent cleaning is performed prior to processes such as painting, plating, inspection, repair, assembly, heat treatment, and machining. The same type of machine that is used in cleaning applications can also be used for drying wet parts (by displacing surface moisture with solvent and evaporating the solvent) and for conditioning the surface of plastic parts. Both nonhalogenated and halogenated solvents may be used in solvent cleaning. Examples of the nonhalogenated solvents typically used are mineral spirits, Stoddard solvents, and alcohols. The five commonly used halogenated solvents used are methylene chloride (MC), perchloroethylene (PCE), trichloroethylene (TCE), 1,1,1-trichloroethane (TCA), and trichlorotrifluoroethane (CFC-113). These five solvents can be used alone or in blends which contain two or more halogenated solvents and sometimes alcohols.

Organic solvent cleaning does not constitute a distinct industrial category but rather is an integral part of many major industries. The five 2-digit Standard Industrial Classification (SIC) codes that use the largest quantities of halogenated solvents for cleaning are: SIC 25 (furniture and fixtures), SIC 34 (fabricated metal products), SIC 36 (electric and electronic equipment), SIC 37 (transportation equipment) and SIC 39 (miscellaneous manufacturing industries). Additional industries that use halogenated solvents in cleaning include SIC 20 (food and kindred products), SIC 33 (primary metals), SIC 35 (nonelectric machinery), and SIC 38 (instruments and clocks). Nonmanufacturing industries such as railroad, bus, aircraft, and truck maintenance facilities; automotive and electric tool repair shops; automobile dealers; and service stations (SIC 40, 41, 42, 45, 49, 55, and 75, respectively) also use organic solvent cleaners.

This chapter describes typical organic solvent cleaning processes and emissions from machines using halogenated solvents. Section 3.2 describes the various types of cleaners. Section 3.3 identifies emission mechanisms and presents test data on cleaner emission rates. Section 3.4 discusses typical emission scenarios for vapor cleaners.

3.2 ORGANIC SOLVENT CLEANING PROCESSES

There are three basic types of solvent cleaning equipment: open top vapor cleaners (OTVC's), in-line (cold and vapor) cleaners, and batch cold cleaners. The vast majority of halogenated solvent use is in vapor cleaning, both open top and in-line. The primary solvents used in batch cold cleaners are mineral spirits, Stoddard solvents, and alcohols. Very little halogenated solvent use has been identified in batch cold cleaning.

In 1987, an estimated 150,000 metric tons (Mg) of halogenated solvents were used by OTVC's; 50,000 Mg by in-line vapor cleaners; 30,000 Mg by in-line cold cleaners; and 2,000 Mg by cold cleaners. Furthermore, an estimated 25,000 to 35,000 OTVC's; 2,000 to 3,000 in-line vapor cleaners; 500 to 1,000 in-line cold cleaners; and 100,000 cold cleaners were using halogenated solvents in 1987.[1]

A description of OTVC's is presented in Section 3.2.1. Section 3.2.2 presents information on in-line cleaners while Section 3.3.3 describes cold cleaners.

3.2.1 Open Top Vapor Cleaners

Open top vapor cleaners are used primarily in metalworking operations and other manufacturing facilities. They are seldom used for ordinary maintenance cleaning because cold cleaners using petroleum distillate solvents can usually perform this type of cleaning at a lower cost. Exceptions include maintenance cleaning of electronic components, small equipment parts, and aircraft parts, where a high degree of cleanliness is needed.

A basic OTVC, shown in Figure 3-1, is a tank designed to generate and contain solvent vapor. At least one section of the tank is equipped with a heating system that uses steam, electricity, hot water, or heat pumps to boil liquid solvent. As the solvent boils, dense solvent vapors rise and displace the air inside the tank. The solvent vapors rise to the level of the primary condensing coils. Coolant (such as water) is circulated or recirculated through the condensing coils to provide continuous condensation of rising solvent vapors and, thereby, create a controlled vapor zone which prevents vapors from escaping the tank. Condensing coils generally are

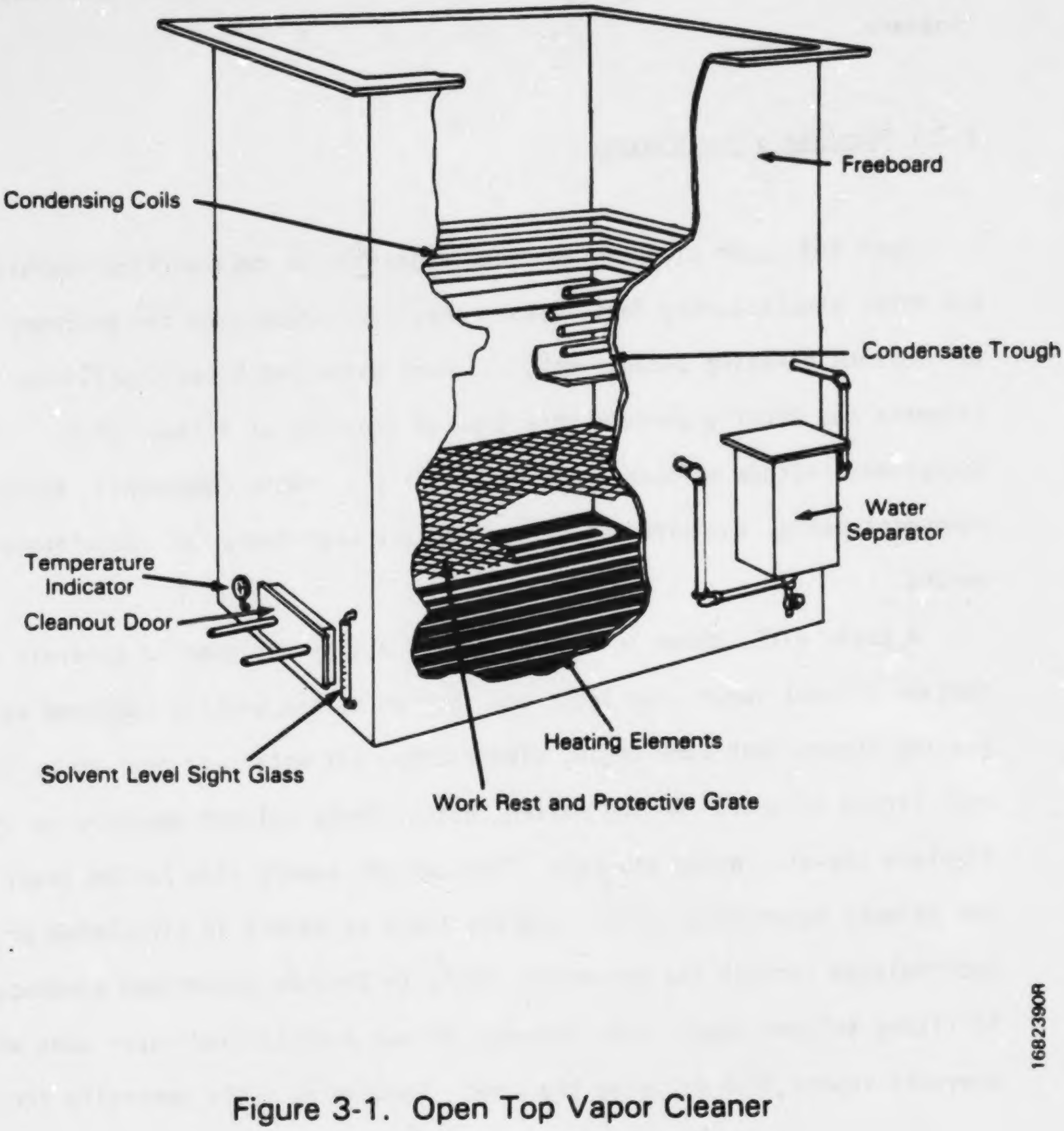

Freeboard
Condensing Coils
Condensate Trough
Water Separator
Temperature Indicator
Cleanout Door
Solvent Level Sight Glass
Heating Elements
Work Rest and Protective Grate
1682390R

Figure 3-1. Open Top Vapor Cleaner

located around the periphery of the inside walls of the cleaner, although in some equipment they consist of offset coils on one end or side of the cleaner.

All machines have covers of varying design to limit solvent losses and contamination during downtime or idle time. Additional control of the solvent vapor is provided by the freeboard, which is that part of the tank wall extending from the top of the solvent vapor level to the tank lip. The freeboard ratio (FBR), or ratio of freeboard height to machine width (smaller dimension of vapor-air interface area), usually ranges from 0.75 to 1.0, depending on the manufacturer's design. The freeboard ratio can be as low as 0.5 on some older machines. Air currents within an OTVC can cause excessive solvent emissions. Increasing the freeboard ratio reduces the disturbance of the vapor zone due to workplace air currents and slows solvent diffusion out of the machine.

Moisture may enter the OTVC on workloads and also and can condense from ambient air on primary cooling coils or freeboard refrigeration coils along with solvent vapors. If allowed to accumulate, water in an OTVC will lead to higher emissions and may contribute to solvent decomposition and corrosion in the cleaner. Therefore, nearly all vapor cleaners are equipped with a water separator based on the principle depicted in Figure 3-2. The condensed mixture of water and solvent is collected in a trough below the condenser coils and directed to the water separator. The water separator is a simple container in which the water phase (being essentially immiscible with and less dense than halogenated solvents) separates from liquid solvent. The water is directed to disposal while solvent is allowed to

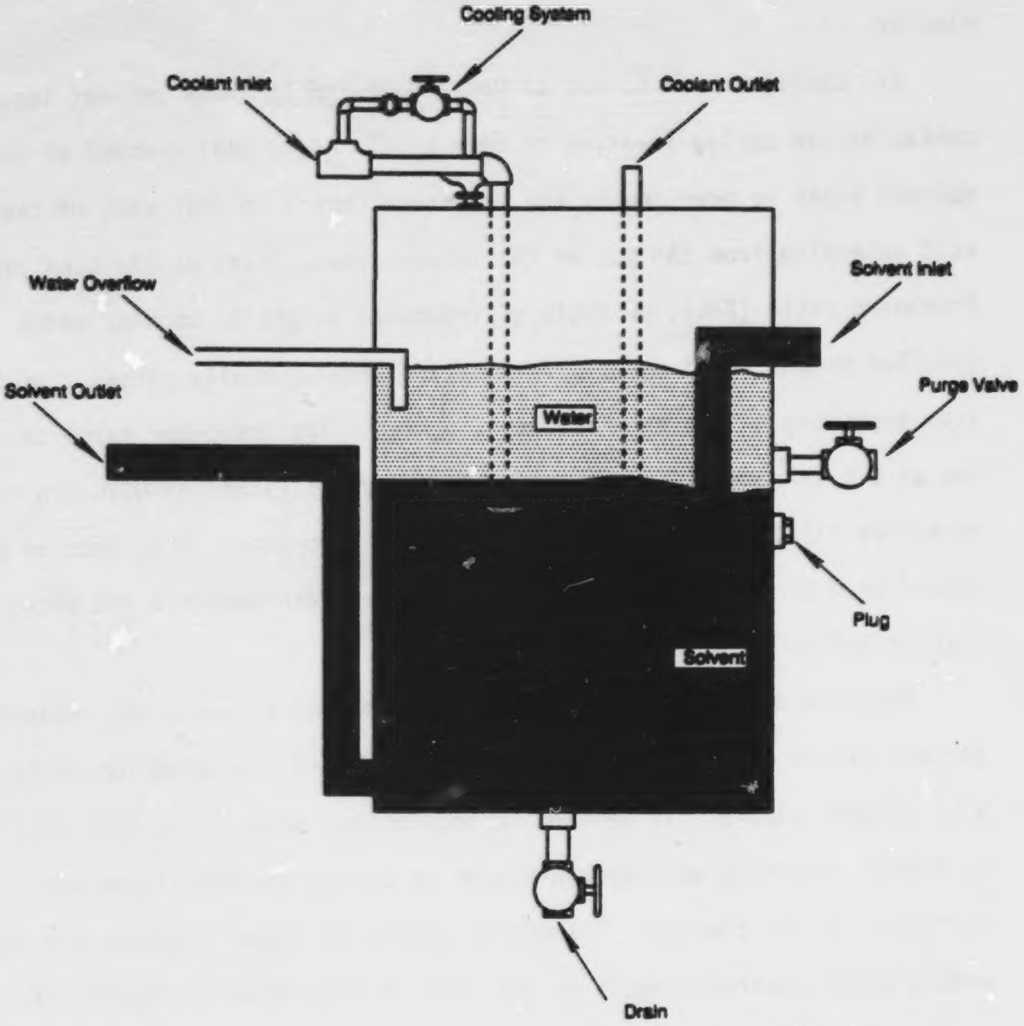

Cooling System
Coolant Inlet
Coolant Outlet
Solvent Inlet
Water Overflow
Solvent Outlet
Purge Valve
Water
Plug
Solvent
Drain
1992773R

Figure 3-2. Water Separator with Cooling Coil

return to the cleaner. Cooling coils may be used inside the separator to cool condensed solvent and enhance solvent/water separation.

To further reduce water contamination or to replace the water separator, some manufacturers produce machines using a canister of desiccant, such as a molecular sieve. Use of dessicants prevents prolonged contact between water and solvent, which can result in removal of water-soluble stabilizers or co-solvents (such as alcohols) from certain solvents and blends. Dessicants also prevent corrosion due to hydrolysis of the solvent.

During the vapor cleaning operation, solvent vapors condense on the cooler workload entering the vapor zone. Condensing solvent dissolves some contaminants and flushes both dissolved and undissolved soils from the workload. Condensed solvent and dissolved or entrained contaminants then drain back into the sump below. When the temperature of the workload reaches that of the vapor, condensation ceases and the vapor phase cleaning process is complete.

Organic impurities (greases, soils, etc.) cleaned from parts will accumulate in the solvent sump. However, they do not appreciably contaminate the solvent vapors because of their higher boiling points. Since the solvent vapor remains relatively pure, solvent can be used for longer periods with vapor cleaning than with cold cleaning where the solvent more quickly becomes contaminated with dissolved and suspended impurities. Eventually, accumulated impurities will compromise the performance or safety of vapor cleaners. To avoid these problems, contaminated solvent is periodically drained from the machine and replaced with fresh solvent.

Alternatively, a still adjacent to the cleaner can be used to extract soils building up in the solvent sump and return clean solvent to the machine. The solvent feed system to the still can include a filter to remove insolubles such as metal fines. Using a still can increase the useful life of solvent and will concentrate the impurities. The lower volume, concentrated waste stream from the still will be less expensive to properly dispose of. Waste streams from solvent cleaning operations are considered hazardous wastes under the EPA's regulations implementing the Resource Conservation and Recovery Act (RCRA).

Variations in design of vapor cleaners reflect their many industrial applications. Workload characteristics and the degree of cleanliness required by the particular application dictate many additional features on the basic model. Additional examples of vapor cleaners are shown in Figures 3-3 and 3-4. These figures show OTVC's with two chambers: one for generating the solvent vapor, the other for immersion cleaning or for spraying applications.

One OTVC design variation is an immersion-vaporspray cycle. In this design, the workload is lowered into a warm or boiling immersion compartment for precleaning. The immersion compartment may be equipped with ultrasonics. In a machine using ultrasonics, high frequency sound waves are used to produce pressure waves in the liquid solvent. In areas of low pressure within the liquid, minute vapor pockets are formed. These pockets collapse as the pressure in the zone cycles to high pressure. The constant creation and collapse of these vapor pockets (called cavitation) provides a scrubbing action to aid cleaning. Ultrasonically agitated liquids often

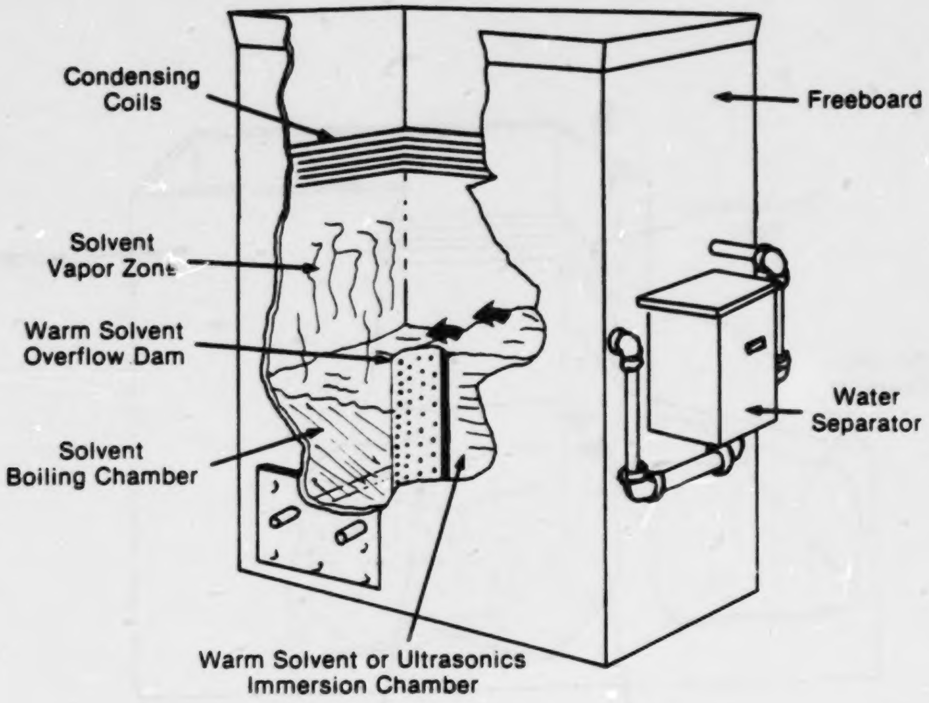

Condensing Coils
Freeboard
Solvent Vapor Zone
Warm Solvent Overflow Dam
Water Separator
Solvent Boiling Chamber
Warm Solvent or Ultrasonics Immersion Chamber

Figure 3-3. Two Compartment Vapor Cleaner

0270726R

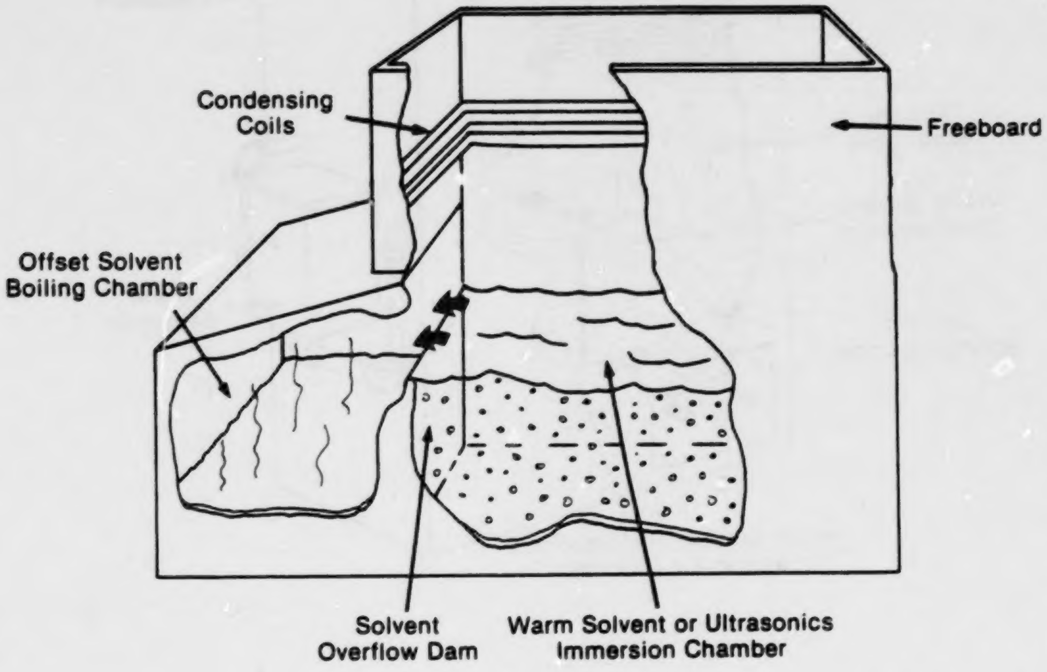

Condensing Coils
Freeboard
Offset Solvent Boiling Chamber
Solvent Overflow Dam
Warm Solvent or Ultrasonics Immersion Chamber

Figure 3-4. Two Compartment Vapor Cleaner with Offset Boiling Chamber

0270725R

need to be heated to specific temperatures to achieve optimum cavitation. After this first stage of cleaning is completed, the workload is cleaned in a vapor section and then sprayed with solvent. Many other cleaning cycles are possible, some of which incorporate non-boiling solvent sections with vapor sections. Spraying may not be necessary or desirable for some applications.

Another common variation in design is a vapor-spray-vapor cycle. In this design, the workload is lowered into the vapor zone where the condensing solvent performs the preliminary cleaning. After condensation ceases, the workload is sprayed with warm solvent. The pressure of the spray aids in physical removal of soil. In some cases, the warm spray may be cooler than the workload and will lower the workload temperature promoting further solvent condensation on the workload. The spray nozzle must be below the vapor line to avoid spraying solvent directly to the atmosphere and directed downward to avoid turbulence at the air/solvent vapor interface.

Lip or slot exhausts, such as shown in Figure 3-5, are designed to capture solvent vapors escaping from the OTVC and carry them away from the operating personnel. These exhaust systems disturb the vapor zone or enhance diffusion, thereby increasing solvent losses. The increased losses can be significant. In properly designed lip exhaust systems, the cover closes below the lip exhaust inlet level. The effect of lip exhausts is discussed further in Chapter 4.

Parts cleaning in an OTVC can be performed either manually or with the use of an automated parts handling system. In manual operation, the

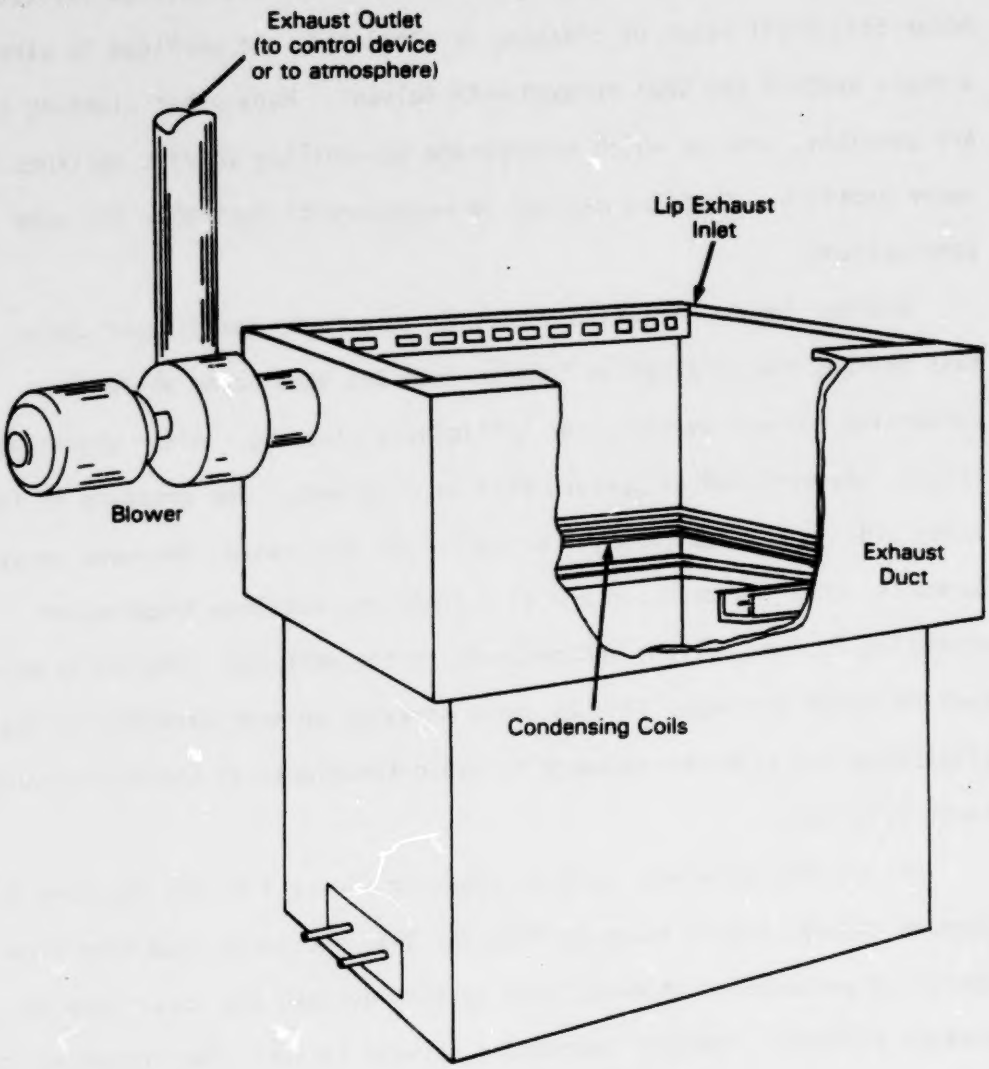

Exhaust Outlet
(to control device
or to atmosphere)
Lip Exhaust
Inlet
Blower
Exhaust
Duct
Condensing Coils
1692595R

Figure 3-5. Open Top Vapor Cleaner with Lip Exhaust

attendant must lower the parts basket into the cleaner and remove the basket once the cleaning has been completed. An electrically operated parts handling system can be operated by push buttons or some can be programmed to cycle parts through the cleaning cycle automatically. With a hoist, the speed of part entry and removal can be controlled and will be consistent from cycle to cycle.

3.2.2 In-line Cleaners

In-line cleaners (also called conveyorized cleaners) employ automated load on a continuous basis. Although in-line cleaners can operate in the vapor or non-vapor phase, the majority of all in-line machines using halogenated solvents are vapor cleaners. A continuous or multiple-batch loading system greatly reduces manual parts handling associated with open top vapor cleaning or cold cleaning. The same cleaning techniques are used in in-line cleaning but usually on a larger scale than with open top units.

In-line cleaners are nearly always enclosed, except for parts/conveyor inlet and exit openings, to help control solvent losses from the system. In-line cleaners are used by a broad spectrum of industries but are most often found in plants where there is a constant stream of parts to be cleaned, where the advantages of continuous cleaning outweigh the lower capital cost of the batch loaded OTVC. Usually, an in-line cleaner is individually designed for a specific workload and production rate situation, rather than being an "off the shelf" item.

There are five main types of in-line cleaners using the halogenated solvents: cross-rod, monorail, belt, strip, and printed circuit board processing equipment (photoresist strippers, flux cleaners, and developers). While most of these may be used with cold or vaporized solvent, the last two are almost always vapor cleaners. The photoresist strippers are typically cold cleaners.

The cross-rod cleaner (Figure 3-6) obtains its name from the rods from which parts baskets are suspended as they are conveyed through the machine by a pair of power-driven chains. The parts are contained in pendant baskets or, where tumbling of the parts is desired, perforated or wire mesh cylinders. These cylinders may be rotated within the liquid solvent and/or the vapor zone. This type of equipment lends itself particularly well to handling small parts that need to be immersed in solvent for satisfactory cleaning or which require tumbling to drain solvent from cavities and/or to remove metal chips.

A monorail vapor cleaner (Figure 3-7) is usually chosen when the parts to be cleaned are being transported between manufacturing operations on a monorail conveyor. The monorail cleaner is well suited to automatic cleaning with solvent spray and vapor. It can be of the straight-through design illustrated or can incorporate a u-turn within the machine so that parts exit through an opening parallel to the entrance opening. The u-turn monorail cleaner benefits from lower vapor loss because the design eliminates the possibility of drafts flowing through the machine.

Both the belt cleaner (Figure 3-8) and the strip cleaner are designed to allow simple and rapid loading and unloading of parts. A belt cleaner conveys parts through a long and narrow boiling chamber in which the parts are cleaned either by the condensing vapor or by immersion in the solvent sump. The strip cleaner is similar to the belt cleaner except that the

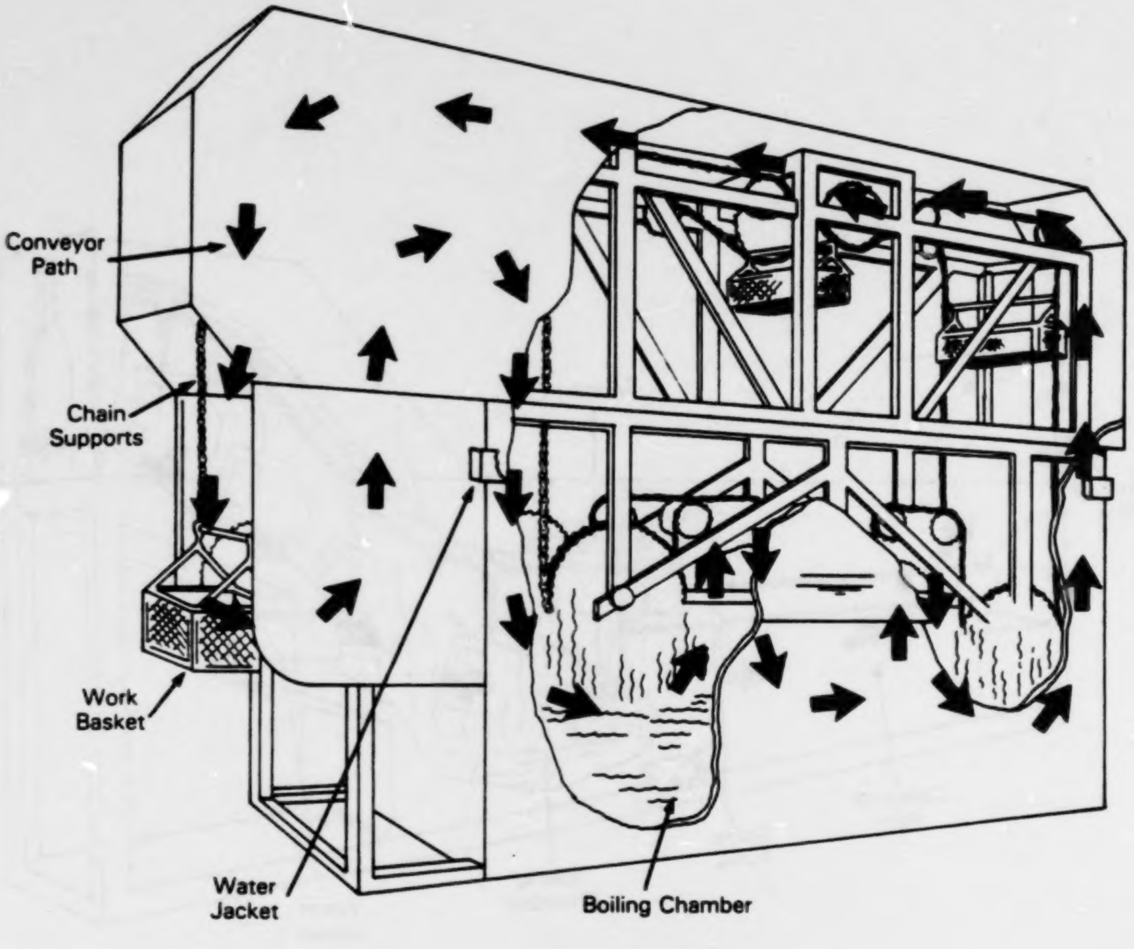

Conveyor Path
Chain Supports
Work Basket
Water Jacket
Boiling Chamber

Figure 3-6. Cross-rod In-line Cleaner

1682393R

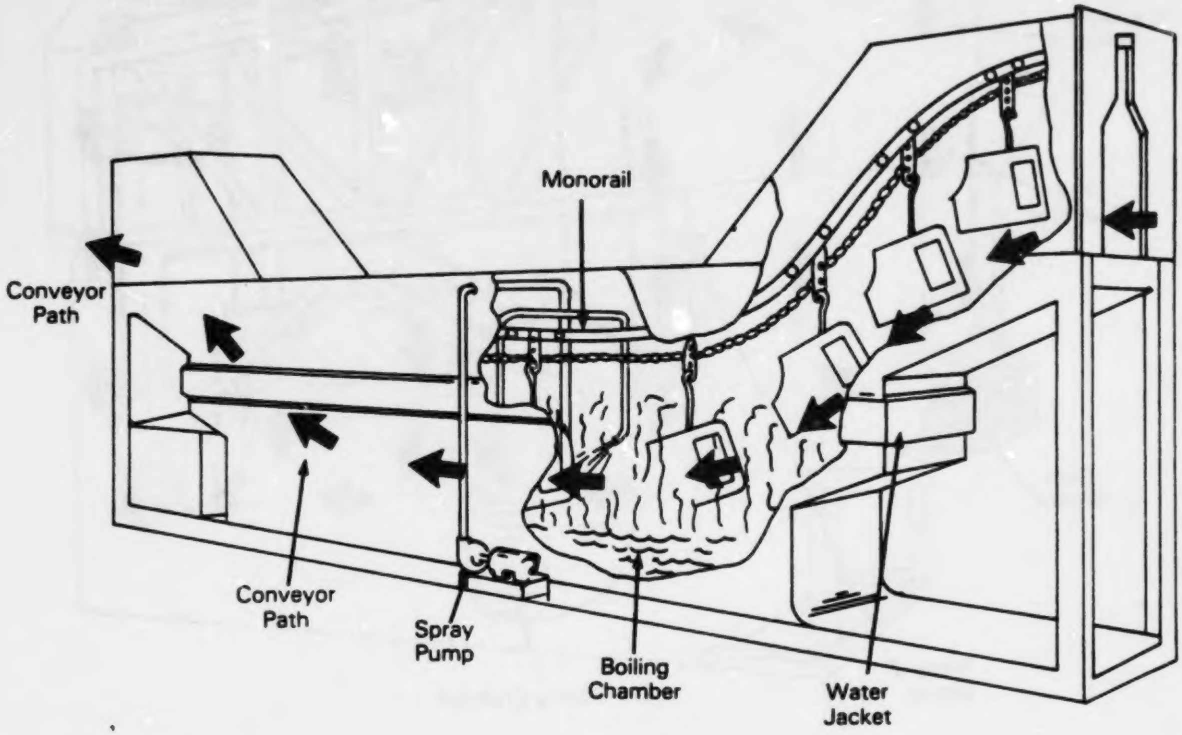

Monorail
Conveyor Path
Conveyor Path
Spray Pump
Boiling Chamber
Water Jacket

Figure 3-7. Monorail In-line Cleaner

1682394R

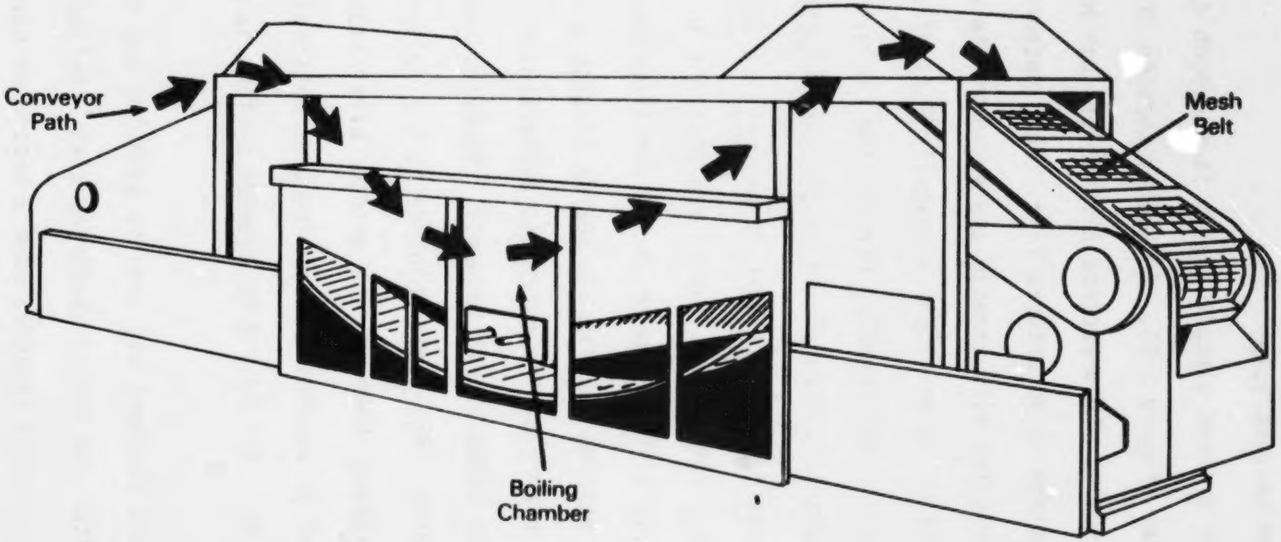

Conveyor Path
Mesh Belt
Boiling Chamber

Figure 3-8. Mesh Belt In-line Cleaner

1682397R

strip itself is the material being cleaned. As with the belt cleaner, the material in a strip cleaner can be cleaned by the condensing vapor or by immersion in the solvent sump.

Cleaning of printed circuit boards is a common application of a type of mesh belt cleaner (Figure 3-9). In the production of printed circuit boards, solvent-based photo-processable resists can be used. The circuit pattern is contained in an artwork film. This pattern is reproduced by projecting ultraviolet rays through the artwork film onto a copper sheet covered with resist. A developer (typically TCA) dissolves the unexposed areas of the resist, and thereby, reveals the circuit pattern. The resist-covered board is then placed in plating solutions to add more metal to the circuit pattern areas. Next, a photoresist stripper dissolves the remaining resist. The circuit boards are then put in an alkaline etching solution to remove all the copper in the noncircuitry areas. The processing is completed by passing the circuit boards through a wave of molten solder.

Due to the nature of the materials being cleaned, photoresist strippers use ambient (room temperature) solvents. Spraying and brushing may be used to enhance cleaning. Methylene chloride is the solvent most often used in photoresist stripping; however, the printed circuit board industry has largely converted to aqueous and semi-aqueous materials to replace the use of both TCA and MC. The switch to aqueous systems is discussed further in Chapter 4.

Circuit board cleaners are used to dissolve and remove flux from the circuit board after the molten soldering step. Unlike photoresist strippers, circuit board cleaners have a heated or boiling sump. However, circuit board cleaning occurs in the liquid solvent (not vapor) phase,

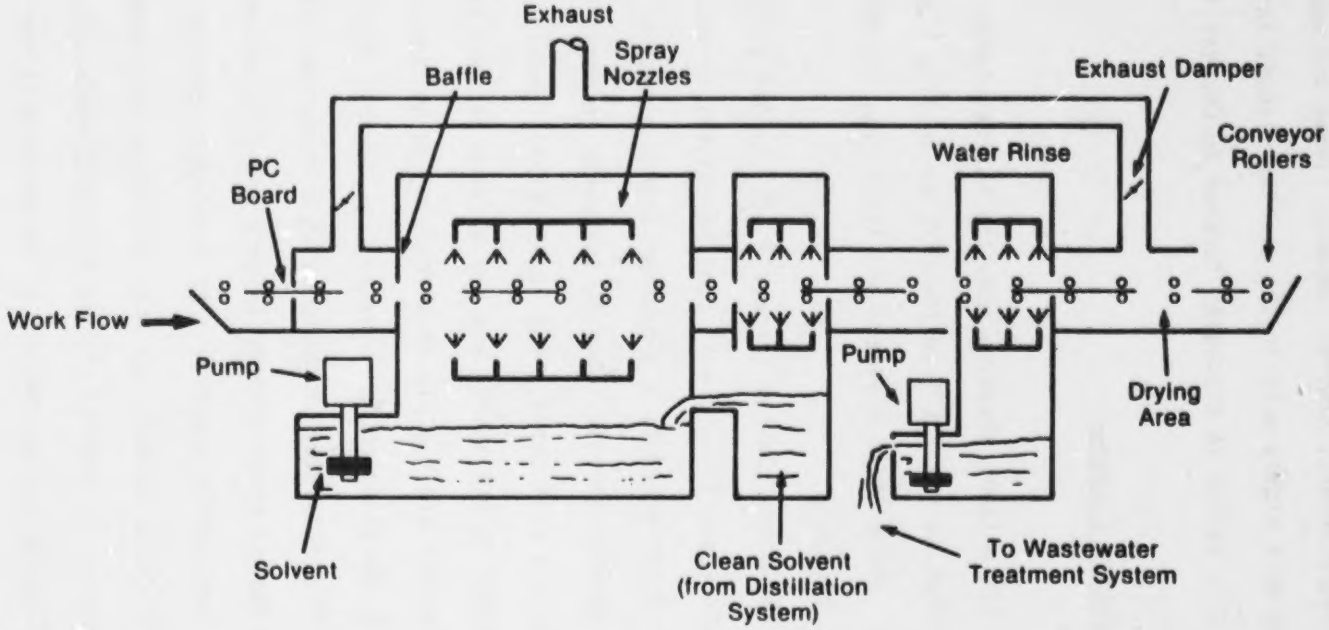

Exhaust
Baffle
Spray Nozzles
Exhaust Damper
PC Board
Water Rinse
Conveyor Rollers
Work Flow
Pump
Pump
Drying Area
Solvent
Clean Solvent (from Distillation System)
To Wastewater Treatment System

Figure 3-9. Schematic Diagram of an In-line Photoresist Stripping Machine

0890744R

although a vapor phase may be present. Circuit board cleaners commonly use chlorofluorocarbons; however, aqueous fluxes and aqueous flux cleaners are becoming more widely used in the printed circuit industry as a replacement. Again, this switch is discussed further in Chapter 4.

3.2.3 Hybrid Cleaners

As the solvent cleaning industry has developed, specialized cleaning devices that do not fit into the OTVC or in-line cleaner categories have emerged. Among these cleaners are the vibra, the ferris wheel, and the carousel cleaners.

In the vibra cleaner (Figure 3-10), soiled parts are fed through a chute into a pan flooded with boiling solvent at the bottom of the cleaner. The pan is connected to a vibrating spiral elevator. Both the pan and spiral elevator vibrate, causing the parts to move from the pan up the spiral to the exit chute. The cooler parts condense solvent vapor as they are vibrated up the spiral and dry as soon as they leave the vapor zone. These cleaners are capable of processing large quantities of small parts. Since the vibrating action creates considerable noise, the equipment must be acoustically insulated or enclosed in a noise-control booth.

The ferris wheel cleaner (Figure 3-11) is one of the least expensive and smallest hybrid cleaners. It is a vapor cleaner and commonly features perforated parts baskets, as does the cross-rod cleaner. As a large gear wheel rotates, it tumbles the perforated baskets attached to it via smaller gears, allowing better contact of the parts with the solvent, and draining cavities that could otherwise retain solvent.

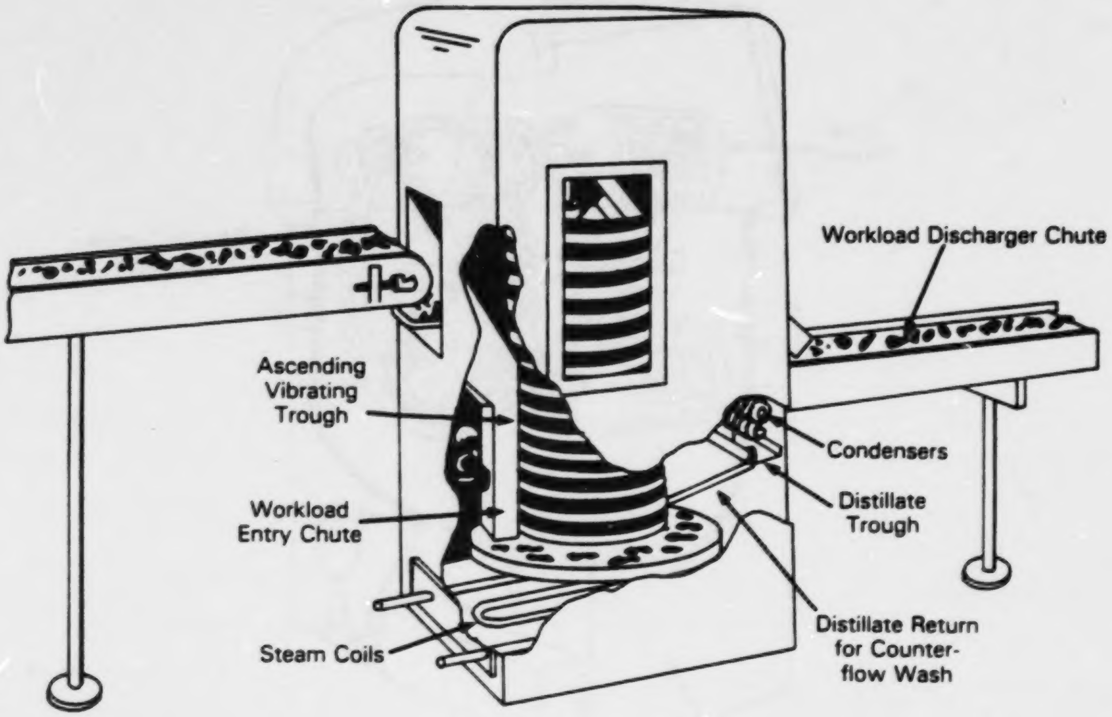
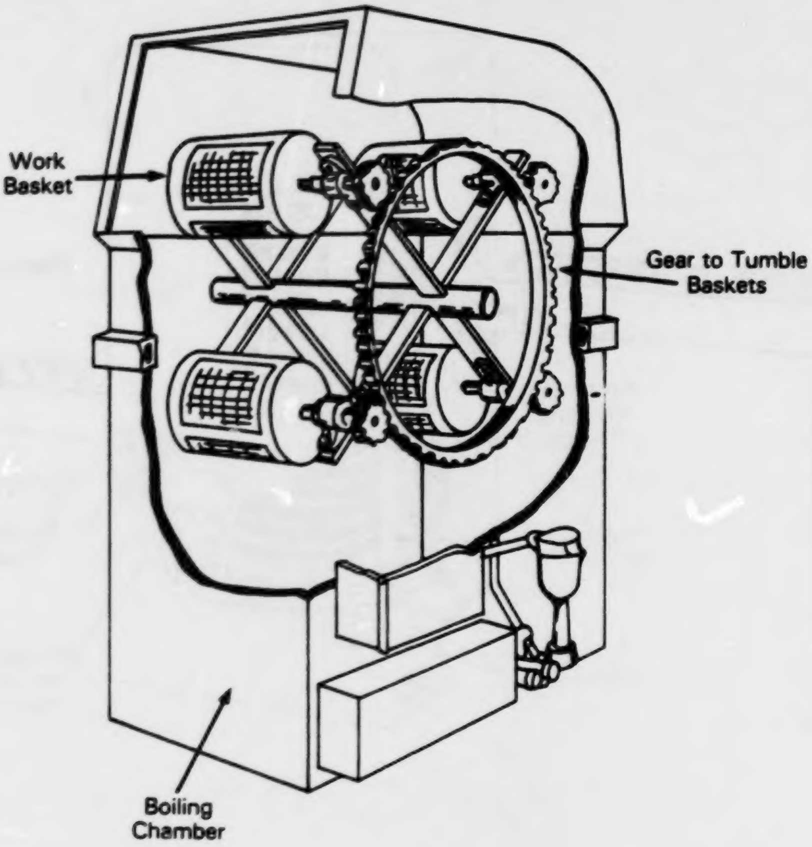

Workload Discharger Chute
Ascending Vibrating Trough
Condensers
Distillate Trough
Workload Entry Chute
Steam Coils
Distillate Return for Counter-flow Wash

Figure 3-10. Vibra Cleaner

1682395R


Work Basket
Gear to Tumble Baskets
Boiling Chamber

1682396R

Figure 3-11. Ferris Wheel Cleaner

The carousel cleaner is a four-chamber machine which is similar to the ferris wheel cleaner except that parts travel on a horizontal plane. The first chamber is the loading area. The remaining three chambers are cleaning units. All cleaning chambers can contain halogenated solvent (typically vapor phase with or without immersion sumps), or one chamber can be used for steam cleaning. Usually, this type of machine is used to clean large parts such as airplane wheels. In operation, a four-arm carousel carries the parts to be cleaned sequentially through each of the four chambers.

3.2.4 Cold Cleaners

Cold cleaners use room temperature liquid solvent for parts cleaning. Most cold cleaners are small maintenance cleaners or parts washers using either aliphatic petroleum distillates such as mineral spirits or sometimes alcohol blends or naphthas. These are not covered in this document.

Cold cleaning operations include spraying, flushing, solvent or parts agitation, wipe cleaning, and immersion. The only machines using halogenated solvent in a cold cleaning application (except for non-vapor in-line cleaning) are of a type called carburetor cleaners. In these cleaners, methylene chloride is blended with other solvents and additives to reduce flammability and increase dissolving power. A typical carburetor cleaner is shown in Figure 3-12. Emissions from these cleaners are typically well controlled because the cleaning solution used contains water which forms as a water layer above the solvent mixture in the tank. The water layer

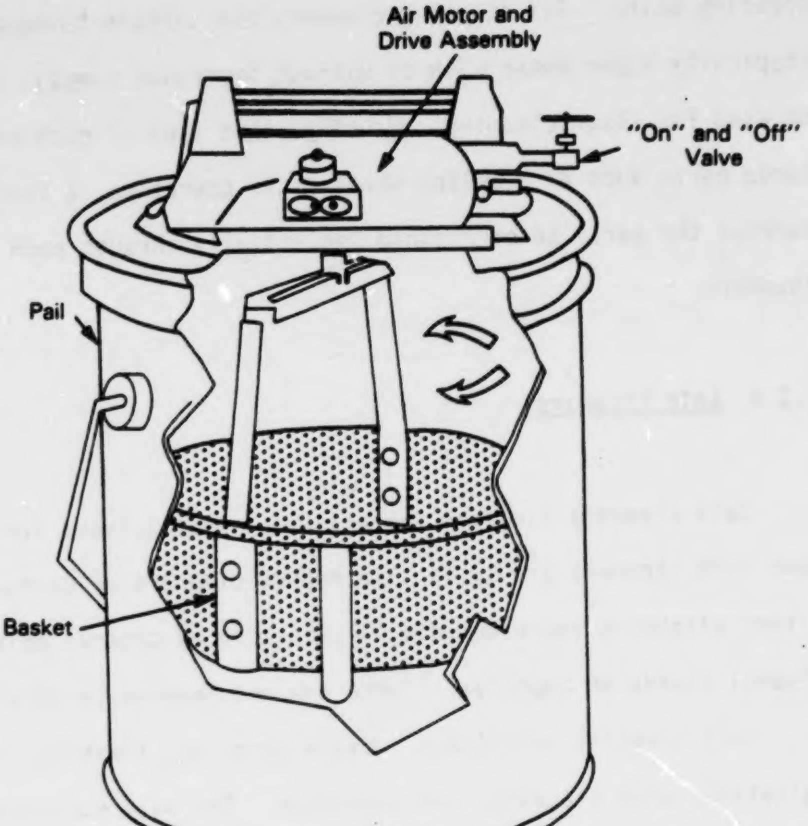

Air Motor and Drive Assembly
"On" and "Off" Valve
Pail
Basket

Figure 3-12. Carburetor Cleaner

1794039R

drastically reduces evaporation of methylene chloride. Although some cold cleaners have been sold in the past for use with halogenated solvents, no manufacturer could be located that is currently marketing machines for use with these solvents, other than those using the carburetor cleaning solutions.

3.3 EMISSION MECHANISMS AND TYPES

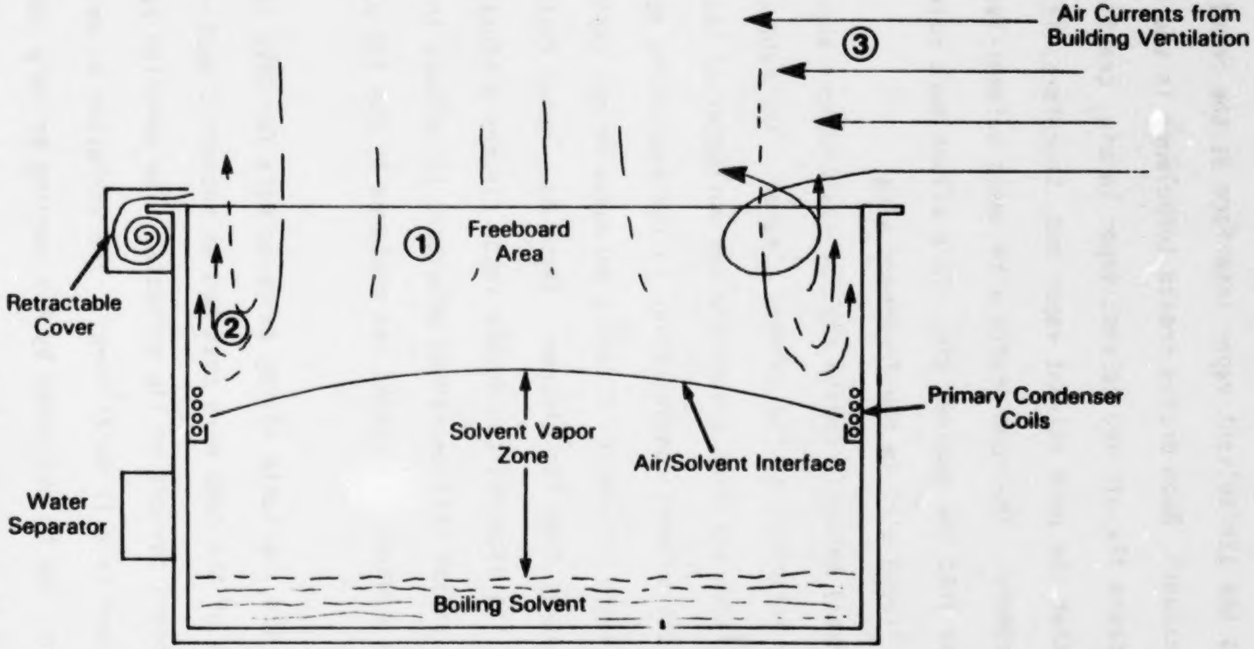
There are many sources of solvent loss to the atmosphere from an organic solvent cleaner. Two significant sources are air/solvent vapor interface losses and workload related losses. Air/solvent vapor interface losses during idling consist of solvent vapor diffusion (or evaporation from liquid solvent in a cold cleaner) and solvent vapor convection induced by warm freeboards. Workload related losses (hereafter called workload losses) are solvent emissions that are created or increased by the introduction and extraction of parts during the cleaning process and by spraying of parts during cleaning (if sprays are used). Other potentially significant losses that contribute to the total solvent emissions from a solvent cleaner include filling/draining losses, wastewater losses, start-up/shutdown losses, downtime losses, and losses from leaks from the cleaner or associated equipment. Diffusion and convection losses are described in Section 3.3.1, while workload and "other" losses are described in Sections 3.3.2 and 3.3.3, respectively.

3.3.1 Air/Solvent Vapor Interface Losses during Idling (Idling Losses)

3.3.1.1 Open Top Vapor Cleaners. The principal emission sources in idling OTVC are shown in Figure 3-13. These losses can be increased dramatically by external factors.

The main source of idling losses from an OTVC is diffusion. Diffusion is the movement of solvent vapors from the vapor zone to the ambient air above. This occurs because molecules of solvent diffuse from the high concentration in the vapor zone to the lower concentration in the air. Diffusion rates are dependent on temperature since molecular activity increases at higher temperatures. An idling machine will reach a point where an equilibrium diffusion rate is established. At this point the emission rate will not fluctuate greatly unless equilibrium conditions are disturbed.

Additional losses can be caused by convection. The heat of the boiling solvent is conducted from the boiling solvent and hot vapor to the walls of the solvent cleaner. This heating of the walls creates a convective flow up along the freeboard carrying solvent vapor out of the cleaner. The amount of convective loss depends on how warm the freeboard walls become. If OTVC walls are kept close to ambient conditions, convective losses will be minimized. Some machines have a water jacket around the outside periphery of the cleaner to help cool the walls of the machine and reduce the convective losses. However, a water jacket is not necessary on all machines. For example, if adequate cooling of the tank walls is provided by primary coils in contact with the OTVC walls, a water jacket is not necessary.


Air Currents from Building Ventilation
③
Retractable Cover
②
①
Freeboard Area
Primary Condenser Coils
Solvent Vapor Zone
Air/Solvent Interface
Water Separator
Boiling Solvent

1. Diffusion of Solvent from Air/Solvent Vapor Interface
2. Convection of Solvent Vapor up Warm Tank Walls
3. Diffusion and Convection Losses Accelerated by Drafts Across Tank Lip (or by Operation of Lip Exhaust Device)

Figure 3-13. OTVC Idling Emission Sources

1692415R

The diffusion rate equilibrium also can be disturbed if an air flow is introduced across the air/solvent vapor interface as the result of room drafts or a lip exhaust. Room drafts create turbulence in the interface area. This can cause the air and solvent vapor to mix, creating a mixture that is lighter than the pure solvent vapor and, therefore, is more readily lost to the atmosphere. The room drafts also sweep solvent-laden air from the freeboard area into the ambient air. This allows more solvent to diffuse into the "fresh air" in the freeboard area.

Lip (or lateral) exhausts create similar disturbances across the air/solvent vapor interface of the solvent cleaner. The exhaust system draws in solvent-laden air from around the top perimeter of the solvent cleaner to lower the solvent concentration in the area where operators are working. As discussed in Chapter 4, these exhausts do not capture all of the vapors that escape from the cleaner. Tests have shown that even properly operated lip exhausts can double vapor cleaner diffusion losses. Some lip exhaust systems include carbon adsorbers to collect the exhausted solvent for reuse; however, emissions not captured by the lip exhaust remain uncontrolled.

A summary of the available idling emission data for OTVC is presented in Table 3-1. All of the data were obtained on uncovered machines with no refrigerated freeboard devices or lip exhausts. The emission rates range from 0.06 lb/ft^2/hour to 0.17 lb/ft^2/hour. The variation in emission rates for the same solvent can be explained by the varying primary condensing temperatures during these tests. Emission rates are lowest in tests where the primary condensing temperature of the cleaner is lowest. The use of a reduced primary condenser temperature as a control technology is discussed

TABLE 3-1. SUMMARY OF AVAILABLE TESTS - IDLING OTVC's

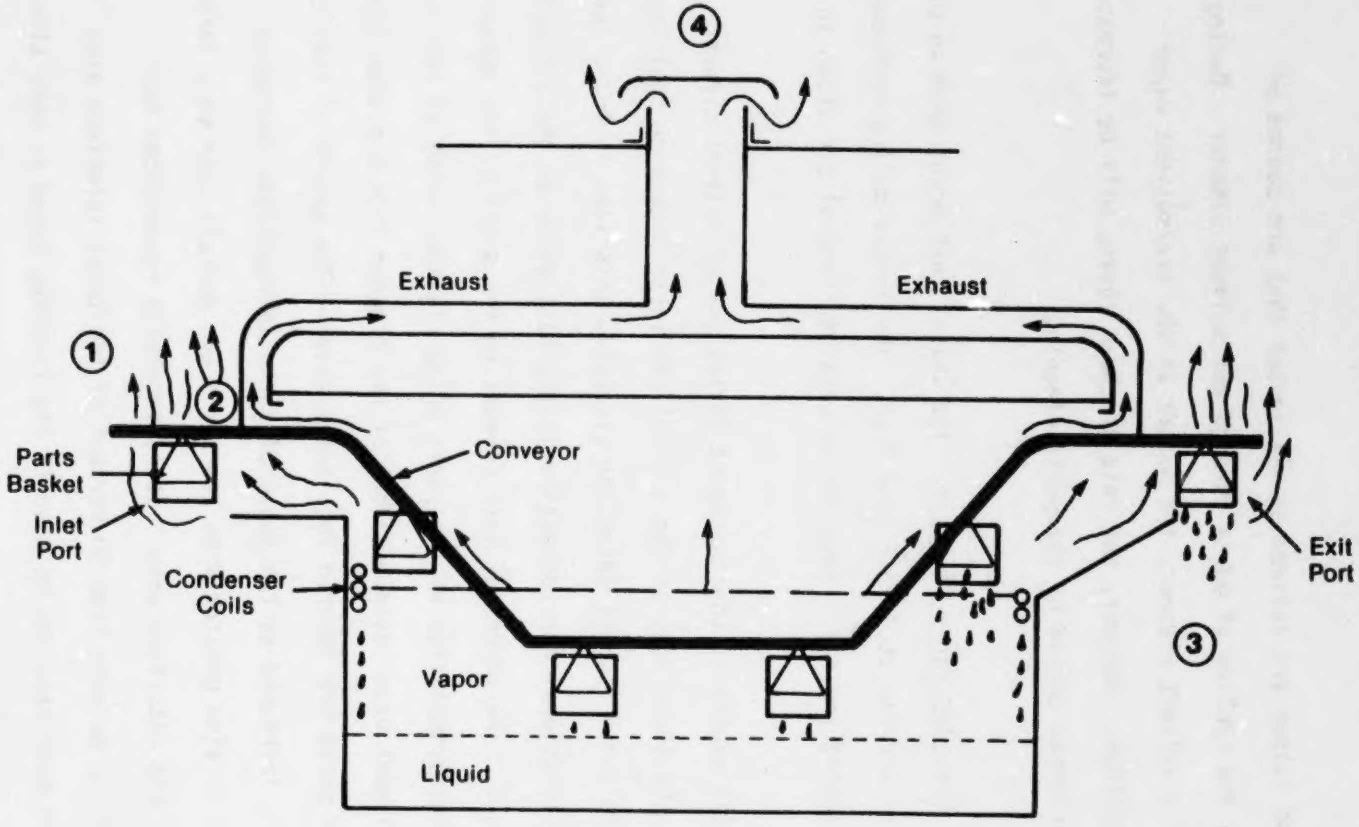
					Conditions		
Test #	Solvent	Cleaner Size (m^2)	FBR[a]	Cleaner Make	Primary Condenser Temperature (oF)	Emission Rate ($lb/ft^2/hr$)	Reference
I-1	Freon-TF	0.3	1.0	Delta Sonics	55	0.060	2
I-2	1,1,1-TCA	0.9	0.7	Auto-Sonics	50	0.087	3
I-3	1,1,1-TCA	0.9	0.7	Auto-Sonics	70	0.120	3
I-4	1,1,1-TCA	0.9	0.7	Auto-Sonics	85	0.143	3
I-5	CFC-113	0.9	0.7	Auto-Sonics	40	0.062	3
I-6	CFC-113	0.9	0.7	Auto-Sonics	50	0.094	3
I-7	CFC-113	0.9	0.7	Auto-Sonics	70	0.169	3

[a] FBR = Freeboard ratio.

in more detail in Chapter 4. At the mid-range primary condensing temperature during the tests (Table 3-1; Tests 3 and 6), the emissions ranged from 0.09 lb/ft^2/hour to 0.12 lb/ft^2/hour.

3.3.1.2 In-line Cleaners. The primary sources of idling losses from in-line vapor cleaners are the same as for OTVC's: convection and diffusion. These types of losses are presented in Figure 3-14, and the mechanisms are described in detail in the previous section. No data were available on idling losses from in-line cleaners. However, the idling diffusional and convective losses from these cleaners would likely be less per unit of air/solvent vapor interface area than an OTVC since the units are almost always enclosed and less subject to drafts.

3.3.1.3 Cold Cleaners. The source of solvent loss from an idle cold cleaner is evaporation from the liquid surface and subsequent diffusion. The rate of solvent loss is solvent dependent and is affected by room drafts. As with OTVC's, room drafts can remove solvent laden air from above the liquid surface, thus increasing equilibrium evaporation rates from quiescent conditions. However, the only identified type of cold cleaner using a halogenated solvent that is currently being manufactured is a carburetor cleaner, which contains some methylene chloride. As mentioned previously, these units typically have water covers. Since the solvent is heavier than and only slightly soluble in water, little solvent reaches the air interface and evaporates.


④
Exhaust
Exhaust
①
②
Parts Basket
Inlet Port
Conveyor
Condenser Coils
Vapor
Liquid
Exit Port
③

1. Diffusion of solvent from air/solvent vapor interface
2. Vapor up warm tank walls
3. Carry-out of liquid solvent on part and subsequent evaporation
4. Roof vent exhaust (where applicable)

0290722R

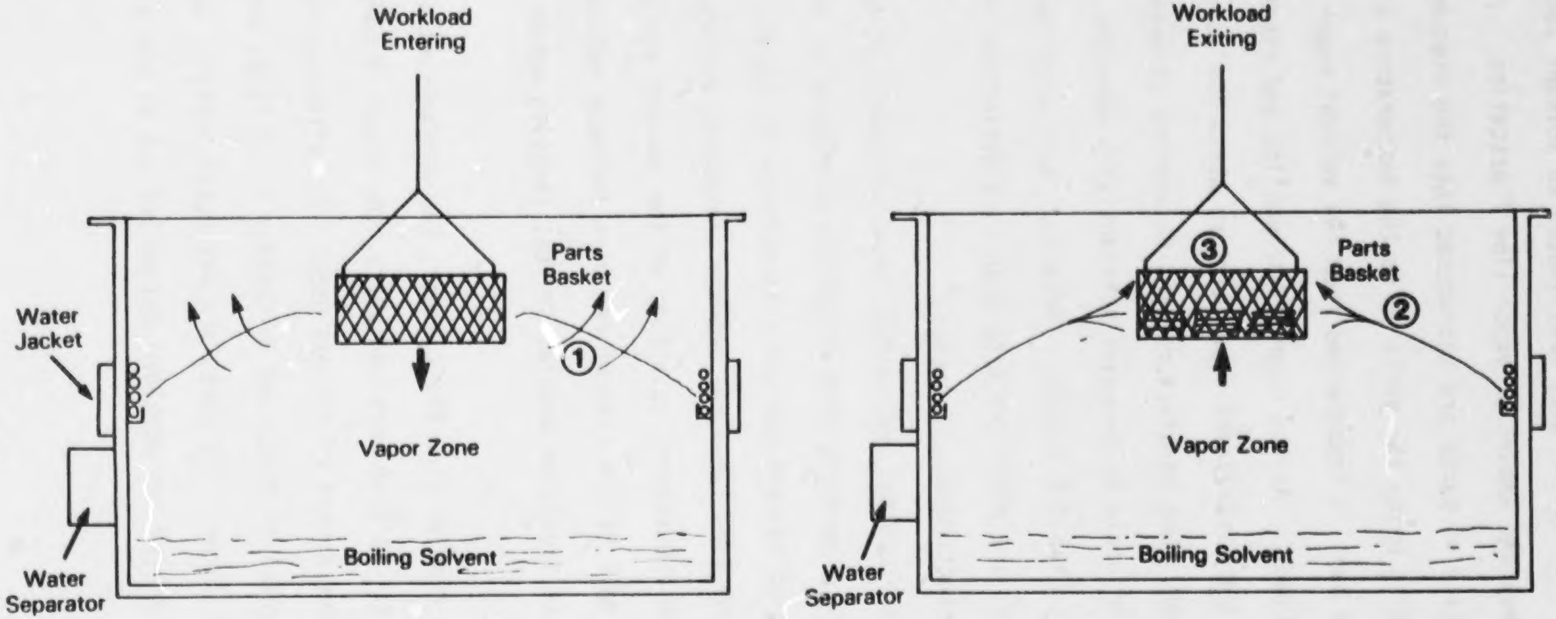
Figure 3-14. In-line Cleaner Emission Sources

3.3.2 Workload Related Losses (Workload Losses)

Workload losses are defined as all losses that are caused or increased by the cycling of parts through the solvent cleaner. During the operation of a solvent cleaner, the losses at the air/solvent vapor interface continue. However, the rate of these losses will be increased due to the disturbances caused by the parts cleaning.

3.3.2.1 Open Top Vapor Cleaners. The losses that occur when an OTVC is cleaning parts are depicted in Figure 3-15. The losses during workload entry and cleaning and the losses during workload removal are shown in the figure.

One of the causes of the increased losses during solvent cleaner operation is the turbulence in the air/solvent vapor interface that occurs when parts and parts baskets enter the cleaner. This loss includes the increase in diffusional and convective losses that occur at the air/solvent vapor interface. The amount of loss depends on the speed of the basket, as well as the characteristics of the parts being cleaned. Part of this loss can be the solvent vapor displaced out of the cleaner from a piston-type effect as the parts are lowered into the cleaner. The amount of loss due to parts entry is increased as the speed of parts introduction increases. The piston effect is also greater when the parts and baskets take up a larger percentage of the interface area. It is generally recommended that workloads take up no more than 50 percent of the total interface area although large workloads can be used if the lowering speed is very slow. Also, if a large part is being lowered into a cleaner, the part can possibly be angled to limit the amount of the piston effect.


Workload
Entering
Parts
Basket
Water
Jacket
①
Vapor Zone
Boiling Solvent
Water
Separator
Workload
Exiting
③
Parts
Basket
②
Vapor Zone
Boiling Solvent
Water
Separator

1. Increased Diffusion and Mixing at Air/Solvent Vapor Interface due to Piston Effect, Disturbance of Vapor Layer, and Spraying
2. Vapor Entrainment and Increased Diffusion and Mixing due to Turbulence
3. Carryout of Solvent on Cleaned Parts

1692416R

Figure 3-15. OTVC Workload Related Emission Sources

Vapor line fluctuation also contributes to solvent loss. Several factors can affect the amount of vapor line fluctuation. If very cold parts or a large quantity of parts are introduced into the cleaner, more heat will be required to bring the parts up to the temperature of the solvent vapor. When the heat is transferred from the solvent vapor to the parts, the vapor line lowers. As the vapor line rebuilds and rises back to its original level, the air/solvent vapor mixture above the layer is displaced out of the cleaner. One manufacturer has determined through testing that solvent loss rates begin to increase substantially when the vapor line is deflected by more than 2.5 inches. These test data also indicated that solvent loss rates are about twice as high at a deflection of 10 inches as they are at a deflection of 2.5 inches.[4]

During parts cleaning, additional losses can occur if sprays are used to aid in cleaning. Spraying from either fixed nozzles or spray wands is common. The sprayed solvent can cause turbulence in the air/solvent vapor interface and vapor line lowering, thereby increasing emissions. If the spray has too high a pressure, splashing of the solvent against the parts, parts basket, or wall of the cleaner can also increase emissions. Both of these spray sources should be mounted so that spraying occurs only beneath the vapor zone.

As parts are removed from the cleaner, the air/solvent vapor interface again is disturbed. As with workload entry, the speed of workload removal directly affects the amount of solvent loss. The effect of parts movement rate on emission rates is discussed in Chapter 4. A large portion of this loss is vapor entrainment. If parts are extracted rapidly, solvent vapor will be entrained behind the workload and pulled out of the cleaner (wake effect).

A final source of loss during workload removal is liquid dragout. This includes liquid pooled in cavities or on flat horizontal surfaces of the parts as well as the solvent film remaining on all surfaces of clean parts as they leave the cleaner. If the workload is withdrawn slowly and allowed to dwell in the freeboard area (if needed), then the solvent film and much of the pooled solvent can evaporate before the workload is withdrawn. A significant portion of this evaporated solvent in the freeboard area will sink back into the vapor layer or be condensed on the coils and return to the cleaner. If, however, the workload is withdrawn quickly, most liquid solvent will not evaporate from the parts until after they are withdrawn from the cleaner. It is very difficult to remove parts slowly by manual operation. Generally, manually operated cleaners will have high workload losses, and these losses will dominate other losses from the machine.

A summary of the available data on working emission rates (i.e., diffusion/convection and workload losses combined) is presented in Table 3-2. The emission rates range from 0.063 lb/ft^2/hour to 0.775 lb/ft^2/hour, with most data in the range of about 0.1 to 0.3 lb/ft^2/hr. The large variability in the data is due to the wide range of operating parameters during the tests. Unlike idling emissions, which are more a factor of the machine design, workload emissions are largely a factor of the operating parameters previously discussed in this section. The speed of parts movement in many of the tests is unknown. All of these test were performed using electric hoists for parts entry and removal. Test results with manually operated machines would be significantly higher because it is difficult to impossible for a human operator to consistently achieve the low workload related losses exhibited by hoists. As stated

TABLE 3-2. SUMMARY OF EMISSION TESTS ON WORKING OTVC's

Test #	Solvent	Cleaner Size (m^2)	Cleaner Make	Air Speed (FPM)	Conditions Primary Condenser Temp.(°F)	FBR[a]	Emission[b] Rate (lb/ft^2/hr)	Reference
1	1,1,1-TCA	1.8	Detrex	calm	--[c]	0.75	0.099	5
2	1,1,1-TCA	1.8	Detrex	130	--[c]	0.75	0.173	5
3	1,1,1-TCA	1.8	Detrex	160	--[c]	0.75	0.233	5
4	1,1,1-TCA	1.4	AutoSonics	--[c]	--[c]	--[c]	0.063	6
5	MC	1.2	Crest	--[c]	--[c]	0.83	0.186	7
6	MC	1.2	Crest	--[c]	--[c]	0.75	0.354	7
7	1,1,1-TCA	0.9	AutoSonics	--[c]	50	--[c]	0.100	3
8	1,1,1-TCA	0.9	AutoSonics	--[c]	70	--[c]	0.140	3
9	1,1,1-TCA	0.9	AutoSonics	--[c]	85	--[c]	0.170	3
10	CFC-113	0.9	AutoSonics	--[c]	40	--[c]	0.090	3
11	CFC-113	0.9	AutoSonics	--[c]	50	--[c]	0.110	3
12	CFC-113	0.9	AutoSonics	--[c]	70	--[c]	0.186	3
13[d]	CFC-113		Branson	--[c]	60	1.0	0.775	8
14	MC blend	0.4	AutoSonics	30	70	0.75	0.220	9
15	MC	0.4	AutoSonics	30	70	0.75	0.180	9
16	CFC-113	0.4	AutoSonics	30	70	0.75	0.165	9
17	MC blend	0.4	AutoSonics	30	70	0.75	0.125	9
18	1,1,1-TCA	0.4	AutoSonics	30	70	0.75	0.112	9
19	TCE	0.4	AutoSonics	30	70	0.75	0.080	9
20	MC blend	0.4	AutoSonics	30	70	1.0	0.175	9
21	MC	0.4	AutoSonics	30	70	1.0	0.145	9
22	CFC-113	0.4	AutoSonics	30	70	1.0	0.132	9
23	MC blend	0.4	AutoSonics	30	70	1.0	0.100	9
24	1,1,1-TCA	0.4	AutoSonics	30	70	1.0	0.092	9
25	TCE	0.4	AutoSonics	30	70	1.0	0.065	9

[a] FBR = freeboard ratio.

[b] "Working" emissions include diffusion, convection, and workload losses as described in Sections 3.3.1 and 3.3.2, but not leaks, solvent transfer losses or downtime losses.

[c] Information unknown or not available.

[d] Constant cycling of parts into and out of machine and use of perforated metal basket that retained significant solvent upon exit from machine account for elevated emission number.

above, the speed of the parts can directly affect the emissions from a cleaner. Furthermore, these tests also included a wide range of room air speeds, which can also affect emission rates. In contrast, the tests of idling rates did not include different draft speeds. Finally, the tests in Table 3-2 did not include lip exhausts, which would greatly increase emissions. A more complete discussion of the effects of operating parameters on emission rates is presented in Chapter 4.

3.3.2.2 In-line Cleaners. The principal sources of workload emissions from in-line cleaners are presented in Figure 3-14. Many of the losses are similar to the losses from OTVC's. Since in-line systems are automated, the workload losses are less on a per part basis than in a manually operated OTVC. However, due to the large volume of parts cleaned in an in-line system, overall losses are typically higher from in-line cleaners than from OTVC's.

The loss due to turbulence at the air/solvent vapor interface (air/solvent interface with in-line cold cleaners) caused by part entry and exit is generally less for in-line cleaners than manually operated OTVC's because automated parts handling allows better control of the speeds of parts entry and exit. However, if the conveyor speed is too high, considerable turbulence will be generated, and parts may exit the cleaner wet with solvent. The piston effect is also lessened since in-line machines have large air/solvent vapor interfaces (air/solvent interface with in-line cold cleaners) relative to the size of the parts and baskets. In general, States that have solvent cleaner regulations limit the conveyor speed to 11 feet per minute (fpm).

Solvent loss due to vapor line fluctuation is not a significant problem for in-line vapor cleaners as with OTVC's. Since there is a constant flow of parts into in-line vapor cleaners, the heat balance of the machine can be adjusted to compensate for the constant thermal shock. This practice would tend to limit vapor line fluctuation in these machines.

During parts cleaning, additional losses can occur if spraying is employed. Spraying is done from either fixed nozzles, spray wands or rotating arms. The solvent spray can cause turbulence within the cleaner and thereby increase emissions, although the enclosure around in-line machines would help minimize loss to the atmosphere. The configuration of entry and exit openings will influence the amount of loss from turbulence inside the machine. If the spray pressure is too high, splashing of the solvent against the parts, parts basket, or wall of the cleaner can also increase emissions. Fixed or rotating spray nozzles should be mounted so that spraying occurs only beneath the vapor zone. For in-line cold cleaners, spraying should occur only at a downward angle into the machine unless the spray section is baffled to effectively shield air/solvent interface from the effects of the spray. Some manufacturers have developed cleaners that have high pressure spray zones completely segregated from the air/solvent vapor interface. These machines are discussed in Chapter 4.

As parts are removed from the cleaner, more disturbances of the air/solvent vapor or air/solvent interface can occur. Again, the speed of the parts movement can directly affect the amount of solvent loss. The effect of part movement rate on emission rates is discussed in Chapter 4. Again, the majority of this loss is vapor entrainment. If parts are extracted rapidly, solvent vapor will be entrained behind the workload and pulled out of the cleaner.

Another source of loss during part removal is liquid dragout. This includes liquid solvent pooled in cavities or on flat horizontal surfaces of parts as well as the solvent film remaining on all surfaces of clean parts as they leave the cleaner. As discussed in Section 3.3.2, the speed of part removal can affect these losses. Some in-line cleaners include a drying tunnel to allow for evaporation of solvent before parts exit the cleaner.

Many in-line cleaners also have an exhaust system. This exhaust system (for an example see Figure 3-14) can increase solvent consumption. If solvent in the exhaust is not controlled by a carbon adsorber before being vented to the atmosphere, overall solvent emissions will increase.

3.3.2.3 Cold Cleaners. Workload related losses from cold cleaners are primarily due to carry-out (and subsequent evaporation) of liquid solvent on parts being removed from the machine. Carry-out losses may be substantially reduced by allowing longer drainage time, and by tipping parts to drain solvent-filled cavities before removal from the cleaner.

Other sources of solvent loss during cold cleaning are agitation and spraying. Agitation can increase evaporation from the solvent bath by increasing the effective air/solvent interface area. The amount of solvent loss depends on the rate of agitation. In the case of carburetor cleaners, the water layer over the solvent bath minimizes the loss from increased turbulence. Spraying can increase solvent evaporation by exposing more solvent to the air. The amount of solvent loss from spraying depends on the spray pressure (which influences turbulence and splashing).

3.3.3 Other Losses

In addition to losses attributable to the solvent cleaner when the machine is idling (i.e., turned on and ready to operate) or working (i.e., cleaning a workload), there are several other loss mechanisms that contribute to overall losses from an organic solvent cleaner. These include leaks, start-up losses, filling/draining losses, shutdown/downtime losses, wastewater losses, distillation losses, and losses due to solvent decomposition/waste solvent storage. The magnitude of these losses relative to total losses is dependent on machine design and integrity and operating techniques. For example, poor technique during filling and emptying of the cleaner can cause spills that could amount to a large portion of overall losses from an otherwise well operated and maintained machine. Similarly, a leak that goes undetected and uncorrected can also be a large source of emissions. A brief discussion of these other losses is presented below.

3.3.3.1 Downtime Losses. Downtime losses are defined as solvent loss when the heat to the sump is turned off and the machine is not operated. The losses are due to evaporation of solvent from the liquid solvent surface and subsequent diffusion into the ambient air. These losses can be slowed through use of a tight fitting cover during downtime. However, even with covers in place, the more volatile halogenated solvents will evaporate at significant rates. Relative evaporation rates of the halogenated solvents are presented in Table 3-3. Equipment vendor estimates of downtime losses range from 0.03 $lb/ft^2/hr$ to 0.07 $lb/ft^2/hr$, comparable to the low end of idling loss rates.[11] Losses will be greatest from machines using

TABLE 3-3. HALOGENATED SOLVENT EVAPORATION RATES

Solvent	Relative Evaporation Rate[a] (CCl_4 = 100)
TCE	84
PCE	39
1,1,1-TCA	100
MC	147
CFC-113	170

[a] Reference 10.

solvents with a higher vapor pressure, such as MC, CFC-113, or solvent blends made with MC or CFC-113.

3.3.3.2 Leaks. Loss of solvent through leaks can occur continuously (depending on where the leak is located), whether the machine is turned on or off. Leaks can result from manufacturing defects or from machine use. They can occur from piping connections, cracks in the machine or tank, and gasketed portholes or viewing windows. Often leaks are difficult to detect since the solvent will evaporate quickly when it reaches the atmosphere and may not leave telltale drips or wet areas. Since solvent has a low surface tension, it can escape through cracks that may not be easily visible. These characteristics magnify the chance of leaks becoming a serious source of solvent loss. Many manufacturers leak test their machines before they are sold, but cracks can occur during shipping. If not detected and repaired, leaks can become a major source of solvent loss.

3.3.3.3 Filling/Draining Losses. The loss of solvent during filling and emptying of the solvent cleaner can be a major contributor to overall emissions if not properly performed. Open handling procedures, such as manual filling or emptying machines using open buckets or drums, will cause significant solvent loss and operator exposure. This loss will increase if a large amount of splashing occurs during filling. If solvent is spilled during filling or draining, the operator may be subject to Comprehensive Environmental Response, Composition, and Liability Act (CERCLA) regulations requiring the notification of all spills above reportable quantities.

3.3.3.4 Wastewater Losses. Water separators are typically minor sources of solvent loss on vapor cleaners. The solvent loss occurs when the water is decanted from the separator containing a slight amount of solvent (solvents are slightly soluble in water). Water separators are used to recover solvent from the solvent/water mixture that condenses at the primary chiller or at the refrigerated freeboard device. Freeboard refrigeration devices may increase wastewater loss, if not properly designed, since they condense water vapor from the atmosphere in addition to solvent. However, if a separator is correctly designed, operated and maintained, little solvent will be lost. Wastewater impacts due to the use of a carbon adsorber as a control device to recover solvent are discussed in Chapter 4.

3.3.3.5 Start-up/ Shutdown Losses. The losses that occur during the transition time from when a vapor solvent cleaner is turned on or off to the time when equilibrium is achieved are called start-up and shutdown losses.

Start-up losses are due to pump out of solvent-laden air within the machine after the sump heat has been activated and as the solvent vapor layer is being established. One estimate of start-up losses from a typical vapor cleaner is 3 gallons of solvent per cycle.[12] However, the amount of loss from a cleaner depends on the cleaner size and design.

Shut-down losses are due to evaporation of hot liquid solvent from the sump (after the heat has been turned off and the vapor layer has collapsed) and subsequent diffusion of solvent vapor from the machine. If not controlled, shut-down losses will be significant since the solvent in the machine is near the boiling point at the beginning of the shut-down period.

3.3.3.6 Distillation Losses/Sludge Disposal. Losses occur when spent solvent is regenerated through onsite distillation for reuse. Solvent lost during this process stems from evaporation during transfer to and from the distillation unit or, if a piping system is used, from leaks in the equipment. Solvent may also evaporate from distillation sludge or spent solvent that is removed for disposal.

3.3.3.7 Solvent Decomposition Losses. Certain solvents and blends contain stabilizers which prevent the mixture from turning acidic after reacting with water (where water/solvent contact occurs). If solvent is not properly monitored but allowed to become acidic, the solvent will have to be discarded. Dangerous fumes (chlorine gas, hydrochloric acid) can be emitted from solvent decomposition. Emissions could occur during handling and disposal of the solvent. This solvent would be subject to hazardous waste guidelines under RCRA.

3.4 TYPICAL EMISSION SCENARIOS FOR VAPOR CLEANERS

Idling emission rates and working emission rates can vary considerably from operation to operation depending on cleaning machine design, types of solvent, and operating environment. If the five halogenated solvents are used in identical machines, measured idling emission rates will vary somewhat among the solvents. For example, CFC-113 and MC tend to have higher idling losses than the others. However, machines using these solvents are designed to compensate for this, usually by employing lower primary condensing temperatures. Moreover, working losses from identical machines also show differences by solvent, although the order may be different from that observed in idling emission rate comparisons. The emission rate differences due to solvent characteristics appear to be relatively small and are overshadowed by other factors such as: the amount of room draft the cleaner is exposed to, the type of workload cleaned, hours of operation, and operating practices. Therefore, no attempt is made in this document to define emission rates on a solvent specific basis. The "typical" emission rates developed in this section are meant to be representative of cleaners using any one of the five solvents.

The operating schedule defines the relative amounts of time the machine spends in the idling, working (i.e., cleaning) and downtime modes. For example, a cleaner that is in the working mode for most of the day would emit more than the same cleaner in the idling mode for most of the day. This is due to the fact that the working emission rate for a cleaner is higher than the idling emission rate.

The relative contribution of each emission type (idling, workload, leaks, start-up/shut-down, downtime, etc.) influences the effectiveness of control techniques selected to reduce overall emissions, and thereby solvent consumption, from a cleaner. If the majority of overall emissions are due to idling and downtime losses, then control techniques that reduce those emission types would be relatively more important in determining overall effectiveness of control. Conversely, if the machine is in the working mode most of the time, then controls that reduce workload emissions would dominate the overall effectiveness of all controls.

An example of the variation in solvent cleaner emissions with operating schedule is shown in Table 3-4 for a hypothetical OTVC. In-line vapor cleaner emissions would vary less with operating schedule compared to an OTVC since in-line cleaners presumably clean a continuous stream of parts and, thus, have few idle periods. The estimates of annual solvent emissions in Table 3-4 are meant to represent typical, well-run manual operations and are based on the following parameters:

- An OTVC with no additional controls, some room drafts, 0.75 freeboard ratio, and a primary condenser operating at approximately 75°F.
- Idling losses of 0.15 $lb/ft^2/hr$ (within the range in Table 3-1)
- Working losses of 0.4 $lb/ft^2/hr$
- Downtime losses of 0.03 $lb/ft^2/hr$ (from Reference 2)
- OTVC size of 8.6 ft^2 (from general vendor information)
- Assumed daily operating schedule A of 2-hour working, 6-hour idling, and 16-hour downtime for 250 days per year (24-hour downtime for 105 days per year)
- Assumed operating schedule B of 12-hour working, 4-hour idling, and 8-hour downtime for 250 days per year (24-hour downtime for 105 days per year).

In this example, wastewater losses, leaks, start-up/shutdown losses and solvent/waste solvent transfer losses are not included. These sources can be significant, especially in poorly designed, maintained or operated cleaners.

TABLE 3-4. EXAMPLE OF OPERATING SCHEDULE INFLUENCE ON SOLVENT CLEANER EMISSIONS

Emission Type	Solvent Emission Rate (lb/yr)[a]	
	Schedule A[b]	Schedule B[c]
Idling	2,010 (36%)	1,340 (10%)
Working[d]	1,790 (33%)	10,730 (81%)
Downtime	1,720 (31%)	1,180 (9%)
TOTAL	5,520 (100%)	13,250 (100%)

[a] Based on OTVC size of 8.6 ft^2 ($0.8m^2$).

[b] Assumes daily operation of 2-hour working, 6-hour idling, and 16-hour downtime.

[c] Assumes daily operation of 12-hour working, 4-hour idling, and 8-hour downtime.

[d] Working losses include idling loss and workload related losses (as described in Sections 3.3.1 and 3.3.2, respectively).

[e] Other emission sources, such as leaks and startup/shutdown losses, have not been included in this example but could be significant sources of solvent loss.

3.5 REFERENCES

1. Memorandum from Pandullo, R. F., Radian Corporation, to D. A. Beck, EPA/CPB. February 15, 1989. Estimation of nationwide number of halogenated solvent cleaners and halogenated solvent usage.

2. Letter and attachments from Delta Sonics to D.A. Beck, EPA/CPB, February 1988. 6 pages. Estimation of freon solvent usage in open top series Delta Sonics degreasers.

3. Cool It to Cut Degreasing Cost. American Machinist. November 1982.

4. Trip report. Pandullo, R. F., Radian Corporation, submitted to D.A. Beck, EPA/CPB, Research Triangle Park, NC. January 1989. Summary of visit to Allied Corporation, Buffalo Research Facility.

5. Memorandum from Goodrich, J., Detrex Corporation, to L. Schlossberg, Detrex, Inc. Degreaser emissions control test report.

6. Trip report. Irvin, R., GCA/Technology Division, submitted to D.A. Beck, EPA/CPB, Research Triangle Park, NC. June 14, 1979. Summary of visit to Autosonics, Incorporated.

7. Suprenant, K. S. and D. W. Richards (Dow Chemical Company). Study to Support New Source Performance Standards for Solvent Metal Cleaning Operations. Prepared for U.S. Environmental Protection Agency, Research Triangle Park, NC. April 1976. Contract No. 68-02-1329, Task Order No. 9.

8. Letter and attachments from Polhamus, R. L, Branson Ultrasonics Corporation, to P. A. Cammer, Halogenated Solvents Industry Alliance. February 10, 1988. Automated hoist test data.

9. Reference 4.

10. American Society for Testing and Materials (ASTM). Cold cleaning with halogenated solvents. Philadelphia, Pa. July 1966. p. 9.

11. Reference 2.

12. Trip report. Miller, S. J., Radian Corporation, submitted to D.A. Beck, EPA/CPB. October 19, 1988. Summary of visit to Unique Industries, Sun Valley, CA.

4.0 EMISSION CONTROL TECHNIQUES

4.1 INTRODUCTION

As discussed in detail in Chapter 3, there are several significant sources of solvent loss from cleaners using halogenated solvents. To achieve low emissions during solvent cleaning, owners or operators must consider minimizing loss from each source. Good control can be achieved through use of a cleaning machine incorporating solvent saving features and through implementation of sound operating practices.

Presented in this chapter are solvent control strategies covering both machine design and operating practices. Table 4-1 presents a chapter outline and lists the control techniques studied. For both open top vapor cleaners (OTVC's) and in-line cleaners, there are separate sections devoted to diffusion/convection controls, workload related controls, and control of other fugitive emission sources. Following these sections is a discussion concluding what design elements and operating practices should be incorporated to achieve a very well controlled solvent cleaning operation. Finally, the chapter ends with remarks about alternatives to solvent cleaning with the five common halogenated solvents.

4.2 OPEN TOP VAPOR CLEANERS

As discussed in Chapter 3, OTVC's utilize a heating system to boil liquid solvent which creates a solvent vapor zone for cleaning. The primary condenser contains the vapor zone within the cleaner.

TABLE 4-1. SUMMARY OF SOLVENT CLEANER CONTROL TECHNIQUES

Cleaner Control Technique	Reference Section
OTVC:	
Interface Emission Controls:	4.2.1
Covers	4.2.1.1
Freeboard Refrigeration Devices	4.2.1.2
Refrigerated Primary Condensers	4.2.1.3
Increased Freeboard Ratio	4.2.1.4
Reduced Room Draft/Lip Exhaust Velocities	4.2.1.5
Enclosed Design	4.2.1.6
Carbon Adsorption	4.2.1.7
Workload Emission Controls:	4.2.2
Mechanically Assisted Parts Handling	4.2.2.1
Reduced Parts Movement Speed	4.2.2.2
Carbon Adsorption	4.2.1.7
Hot Vapor Recycle/Superheated Vapor	4.2.2.3
Proper Operating and Maintenance Practices:	4.2.3
IN-LINE	
Interface Emissions Controls:	4.3.1
Minimize Entrance/Exit Openings	4.3.1.1
Carbon Adsorption	4.3.1.2
Freeboard Refrigeration Devices	4.3.1.3
Workload Emissions Controls:	4.3.2
Carbon Adsorption	4.3.1.2
Drying Tunnels	4.3.2.1
Rotating Baskets	4.3.2.2
Hot Vapor Recycle/Superheated Vapor	4.3.2.3
Proper Operating and Maintenance Practices	4.3.3

Standard OTVC models range in size from 2.2 to 48 square feet (0.2 to 4.5 square meters) in air/solvent vapor interface area, although larger custom made units are in use. A typical OTVC has a 0.75 freeboard ratio, a water-cooled primary condenser, a cover used during downtime, and an external water jacket to cool the cleaner walls (see Figure 3-1). Applicable control techniques vary according to the size, design, application, and operation of the OTVC. In general, the emissions reduction efficiency of the various control options depends upon the fraction of time that the OTVC is idling versus processing work since each control has different effects on these emission mechanisms.

The control techniques for OTVC's presented in the following sections include covers, reduced room drafts, refrigerated freeboard devices, refrigerated primary condensers, raised freeboards, carbon adsorbers, electric or mechanically assisted parts handling/reduced part movement speeds, enclosed designs, and selected operating and maintenance practices. A summary of all OTVC emission test data is presented in Tables 4-2 and 4-3. Tests on idling machines are included in Table 4-2, while working machine data are included in Table 4-3. All idling tests are numbered using an "I" prefix. All of these tests were performed by companies that either manufactured solvent cleaning equipment or sold solvents. No standard test methods were used. Each company established its own test procedure. The data and test procedures have been reviewed by EPA and appear to have given valid, repeatable results. In some cases, the test facilities have been visited by EPA personnel. All OTVC test data in Table 4-3, unless otherwise mentioned, are from machines employing automated mechanical systems for parts handling. In many cases, the speed

TABLE 4-2. SUMMARY OF AVAILABLE TESTS - IDLING OTVC's

					Baseline					Controlled						
Test #	Tested Control	Solvent	Cleaner Size (ft^2)	Cleaner Make	Air Speed (fpm)	Cover	FBR	Freeboard Refrigeration	Emission (lb/ft2/hr)	Air Speed (fpm)	Cover	FBR	Freeboard Refrigeration	Emission ($lb/ft^2/hr$)	Control Efficiency*	Reference
I-1	AFC (PC@50F)	Freon-TF	3.3	Delta Sonics	30	open	1.0	off	0.060	30	open	1.0	AFC	0.049	18%	1
I-2	BFC (PC@50F)	Freon-TF	3.2	Delta Sonics	30	open	1.0	off	0.060	30	open	1.0	BFC	0.050	17%	1
I-3	BFC (PC@50F)	TCA	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.087	LE OFF	none	0.7	BFC	0.040	54%	2
I-4	BFC (PC@70F)	TCA	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.120	LE OFF	none	0.7	BFC	0.050	58%	2
I-5	BFC (PC@85F)	TCA	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.143	LE OFF	none	0.7	BFC	0.063	56%	2
I-6	BFC (PC@40F)	CFC-113	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.062	LE OFF	none	0.7	BFC	0.055	11%	2
I-7	BFC (PC@50F)	CFC-113	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.094	LE OFF	none	0.7	BFC	0.070	26%	2
I-8	BFC (PC@70F)	CFC-113	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.169	LE OFF	none	0.7	BFC	0.072	57%	2
I-9	PC-70 F to 40 F	CFC-113	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.169	LE OFF	none	0.7	off	0.062	63%	2
I-11	PC-85 F to 50 F	TCA	9.7	Auto-Sonics	LE OFF	none	0.7	off	0.143	LE OFF	none	0.7	off	0.087	39%	2
I-12	PC-85 F to 50 F	TCA	9.7	Auto-Sonics	LE ON	none	0.7	off	0.211	LE ON	none	0.7	off	0.171	19%	2
I-13	BFC&LipExh P@50F	TCA	9.7	Auto-Sonics	LE ON	none	0.7	off	0.171	LE OFF	none	0.7	BFC	0.040	77%	2
I-14	BFC&LipExh P@70F	TCA	9.7	Auto-Sonics	LE ON	none	0.7	off	0.190	LE OFF	none	0.7	BFC	0.050	74%	2
I-15	BFC&LipExh P@85F	TCA	9.7	Auto-Sonics	LE ON	none	0.7	off	0.211	LE OFF	none	0.7	BFC	0.063	70%	2
I-16	LIP EXH (PC@50F)	TCA	9.7	Auto-Sonics	LE ON	none	0.7	off	0.171	LE OFF	none	0.7	off	0.087	49%	2
I-17	LIP EXH (PC@70F)	TCA	9.7	Auto-Sonics	LE ON	none	0.7	off	0.190	LE OFF	none	0.7	off	0.120	37%	2
I-18	LIP EXH (PC@85F)	TCA	9.7	Auto-Sonics	LE ON	none	0.7	off	0.211	LE OFF	none	0.7	off	0.143	32%	2
I-19	FBR: 0.75->1.0	TCA	8.0	Detrex	calm	none	0.75	off	0.051	off	none	1.0	off	0.054	-6%	3
I-20	FBR: 0.75->1.0	TCA	8.0	Detrex	30-100	none	0.75	off	0.272	off	none	1.0	off	0.167	39%	3

AFC = Above-Freezing Freeboard Refrigeration; BFC = Below-Freezing Freeboard Refrigeration; LE = Lip Exhaust; PC = Primary Condenser (e.g., PC@50F means the primary condenser temperature was 50°F).

*These control efficiency values refer to the percent control of idling emission (i.e., diffusion and convection losses) only.

TABLE 4-3. SUMMARY OF AVAILABLE TESTS - WORKING OTVC's

					Baseline					Controlled						
Test #	Tested Control	Solvent	Cleaner Size (m^2)	Cleaner Make	Air Speed (fpm)	Cover	FBR	Secondary Chiller	Emission (lb/ft^2/hr)	Air Speed (fpm)	Cover	FBR	Secondary Chiller	Emission (lb/ft^2/hr)	Control Efficiency*	Reference
1	AFC	TCA	1.8	Detrex	calm	none	0.75	none	0.099	calm	none	0.75	AF	0.082	18%	4
2	AFC	TCA	1.8	Detrex	130	none	0.75	none	0.173	130	none	0.75	AF	0.105	39%	4
3	AFC	TCA	1.8	Detrex	160	none	0.75	none	0.233	160	none	0.75	AF	0.116	50%	4
4	AFC	TCA	1.4	AutoSonics		none		none	0.063		none		AF	0.040	37%	5
5	AFC	TCE						none	4.30E+06 g/mo				AF	3.60E+06 g/mo	16%	6
6	AFC	TCE						none	6.20E+06 g/mo				AF	3.50E+06 g/mo	44%	6
7	AFC(spray loss)	Freon TF	0.3	DeltaSonics	calm	none	1.0	none	0.0093 lb/ft2/cy		none	1.0	AF	0.0079 lb/ft2/cy	15%	7
8	BFC	---		---	calm			none					BF			8
9	BFC	TCA	1.8	Detrex	30	none	0.75	none	0.099	calm	none	0.75	BF	0.059	41%	4
10	BFC	TCA	1.8	Detrex	130	none	0.75	none	0.173	130	none	0.75	BF	0.091	47%	4
11	BFC	TCA	1.8	Detrex	160	none	0.75	none	0.233	160	none	0.75	BF	0.150	36%	4
12	BFC	TCA	1.4	AutoSonics		none		none	0.063		none		BF	0.011	82%	5
13	BFC	MC	1.2	Crest		manual	0.83	none	0.186		manual	0.83	BF	0.112	40%	3
14	BFC	MC	1.2	Crest		none	0.75	none	0.354		none	0.75	BF	0.254	28%	3
15	BFC (P@50F)	TCA	0.9	AutoSonics	LE OFF	none	0.7	none	0.100	LE OFF	none	0.7	BF	0.053	47%	2
16	BFC (P@70F)	TCA	0.9	AutoSonics	LE OFF	none	0.7	none	0.140	LE OFF	none	0.7	BF	0.070	50%	2
17	BFC (P@85F)	TCA	0.9	AutoSonics	LE OFF	none	0.7	none	0.170	LE OFF	none	0.7	BF	0.082	52%	2
18	BFC (P@40F)	CFC-113	0.9	AutoSonics	LE OFF	none	0.7	none	0.090	LE OFF	none	0.7	BF	0.075	17%	2
19	BFC (P@50F)	CFC-113	0.9	AutoSonics	LE OFF	none	0.7	none	0.110	LE OFF	none	0.7	BF	0.080	27%	2
20	BFC (P@70F)	CFC-113	0.9	AutoSonics	LE OFF	none	0.7	none	0.186	LE OFF	none	0.7	BF	0.110	41%	2
21	(BFC&LipExh,P@50F	TCA	0.9	AutoSonics	LE ON	none	0.7	none	0.219	LE OFF	none	0.7	BF	0.053	76%	2
22	(BFC&LipExh,P@70F	TCA	0.9	AutoSonics	LE ON	none	0.7	none	0.25	LE OFF	none	0.7	BF	0.070	72%	2
23	(BFC&LipExh,P@85F	TCA	0.9	AutoSonics	LE ON	none	0.7	none	0.277	LE OFF	none	0.7	BF	0.082	70%	2
24	DWELL TIME	Freon TF	0.3	DeltaSonics	1.0	none	1.0	none	0.014 lb/cy	1.0	none	1.0	none	0.008 lb/cyc	46%	7
25	HOIST: 11-3	Freon TF	0.3	DeltaSonics	1.0	none	1.0	none	0.039 lb/cy	1.0	none	1.0	none	0.008 lb/cyc	81%	7
26	HOIST: 20-10[a]			Branson	1.0	none	1.0	none	0.775		none	1.0	none	0.555	28%	9
27	(LIP EXH (P@50F)	TCA	0.9	AutoSonics	LE ON	none	0.7	none	0.219	LE OFF	none	0.7	none	0.100	54%	2
28	(LIP EXH (P@70F)	TCA	0.9	AutoSonics	LE ON	none	0.7	none	0.25	LE OFF	none	0.7	none	0.140	44%	2
29	(LIP EXH (P@85F)	TCA	0.9	AutoSonics	LE ON	none	0.7	none	0.277	LE OFF	none	0.7	none	0.160	42%	2
30	PC-70 F to 40 F	CFC-113	0.9	AutoSonics	LE OFF	none	0.7	none	0.186	LE OFF	none	0.7	none	0.090	52%	2
31	PC-85 F to 50 F	TCA	0.9	AutoSonics	LE OFF	none	0.7	none	0.160	LE OFF	none	0.7	none	0.100	38%	2
32	PC-85 F to 50 F	TCA	0.9	AutoSonics	LE ON	none	0.7	none	0.277	LE ON	none	0.7	none	0.219	21%	4
33	PC-70 F to 50 F	TCA	0.9	AutoSonics	LE OFF	none	0.7	none	0.140	LE OFF	none	0.7	none	0.100	29%	4
34	PC-50 F to 40 F	CFC-113	0.9	AutoSonics	LE OFF	none	0.7	none	0.110	LE OFF	none	0.7	none	0.090	18%	4
35	Biparting cover	TCA	1.8	Detrex	30	none	0.75	none	0.099	30	bipart	0.75	none	0.061	38%	4
36	Biparting cover	TCA	1.8	Detrex	100	none	0.75	none	0.121	100	bipart	0.75	none	0.071	41%	4

AFC = Above-Freezing Freeboard Refrigeration; BFC = Below-Freezing Freeboard Refrigeration; LE = Lip Exhaust; PC = Primary Condenser (e.g., PC@50F means the primary condenser temperature was 50°F); unk = information unknown or not available.

*These control efficiency values refer to percent control of working losses (i.e., diffusion/convection losses plus workload related losses). They do not reflect control of other possible emission sources such as: leaks, startup/shutdown losses, solvent transfer losses, and downtime losses.

[a] The relatively high emission rates were due to the configuration of the parts basket (i.e., a large horizontal surface area) and the constant cycling of parts (i.e., no time was allowed for the parts/basket to reach the temperature of the solvent vapor).

TABLE 4-3. SUMMARY OF AVAILABLE TESTS - WORKING OTVC's

					Baseline					Controlled						
Test #	Tested Control	Solvent	Cleaner Size (m^2)	Cleaner Make	Air Speed (fpm)	Cover	FBR	Secondary Chiller	Emission ($lb/ft^2/hr$)	Air Speed (fpm)	Cover	FBR	Secondary Chiller	Emission ($lb/ft^2/hr$)	Control* Efficiency	Reference
37	Biparting cover	TCA	1.8	Detrex	130	none	0.75	none	0.173	130	bipart	0.75	none	0.090	48%	4
38	Biparting cover	TCA	1.8	Detrex	160	none	0.75	none	0.233	160	bipart	0.75	none	0.109	53%	4
39	Biprtng cvr&AFC	TCA	1.8	Detrex	30	none	0.75	none	0.099	30	bipart	0.75	AFC	0.054	45%	4
40	Biprtng cvr&AFC	TCA	1.8	Detrex	100	none	0.75	none	0.121	100	bipart	0.75	AFC	0.070	42%	4
41	Biprtng cvr&AFC	TCA	1.8	Detrex	130	none	0.75	none	0.173	130	bipart	0.75	AFC	0.083	52%	4
42	Biprtng cvr&AFC	TCA	1.8	Detrex	160	none	0.75	none	0.233	160	bipart	0.75	AFC	0.105	55%	4
43	Biprtng cvr&BFC	TCA	1.8	Detrex	30	none	0.75	none	0.099	30	bipart	0.75	BFC	0.055	44%	4
44	Biprtng cvr&BFC	TCA	1.8	Detrex	100	none	0.75	none	0.121	100	bipart	0.75	BFC	0.064	47%	4
45	Biprtng cvr&BFC	TCA	1.8	Detrex	130	none	0.75	none	0.173	130	bipart	0.75	BFC	0.080	54%	4
46	Biprtng cvr&BFC	TCA	1.8	Detrex	160	none	0.75	none	0.233	160	bipart	0.75	BFC	0.078	67%	4
47	FBR: 0.75->1.0	MC blend	0.4	AutoSonics	30	none	0.75	none	0.220	30	none	1.0	none	0.175	20%	10
48	FBR: 0.75->1.0	MC	0.4	AutoSonics	30	none	0.75	none	0.180	30	none	1.0	none	0.145	19%	10
49	FBR: 0.75->1.0	CFC-113	0.4	AutoSonics	30	none	0.75	none	0.165	30	none	1.0	none	0.130	21%	10
50	FBR: 0.75->1.0	MC blend	0.4	AutoSonics	30	none	0.75	none	0.125	30	none	1.0	none	0.100	20%	10
51	FBR: 0.75->1.0	TCA	0.4	AutoSonics	30	none	0.75	none	0.112	30	none	1.0	none	0.090	20%	10
52	FBR: 0.75->1.0	TCE	0.4	AutoSonics	30	none	0.75	none	0.080	30	none	1.0	none	0.065	19%	10
53	FBR: 1.0->1.25	MC blend	0.4	AutoSonics	30	none	1.0	none	0.175	30	none	1.25	none	0.165	6%	10
54	FBR: 1.0->1.25	MC	0.4	AutoSonics	30	none	1.0	none	0.145	30	none	1.25	none	0.135	7%	10
55	FBR: 1.0->1.25	CFC-113	0.4	AutoSonics	30	none	1.0	none	0.132	30	none	1.25	none	0.122	8%	10
56	FBR: 1.0->1.25	MC blend	0.4	AutoSonics	30	none	1.0	none	0.100	30	none	1.25	none	0.092	8%	10
57	FBR: 1.0->1.25	TCA	0.4	AutoSonics	30	none	1.0	none	0.092	30	none	1.25	none	0.083	10%	10
58	FBR: 1.0->1.25	TCE	0.4	AutoSonics	30	none	1.0	none	0.065	30	none	1.25	none	0.059	9%	10
59	Draft 160-calm	TCA	1.8	Detrex	160	none	0.75	none	0.233	30	none	0.75	none	0.099	58%	4
60	Draft 130-calm	TCA	1.8	Detrex	130	none	0.75	none	0.173	30	none	0.75	none	0.099	43%	4

AFC = Above-Freezing Freeboard Refrigeration; BFC = Below-Freezing Freeboard Refrigeration; LE = Lip Exhaust.

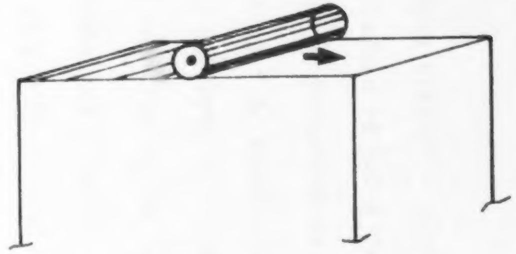
*These control efficiency values refer to percent control of working losses (i.e., diffusion/convection losses plus workload related losses). They do not reflect control of other possible emission sources such as: leaks, startup/shutdown losses, solvent transfer losses, and downtime losses.

of parts movement is unknown; however, it was likely 11 fpm or less in all cases. In almost all cases, workloads used for these tests can be described as inherently producing low carryout losses. Therefore, emission rates would likely be higher from machines in regular industrial applications. Inferences on control efficiencies that can be drawn from these data are discussed in the following sections.

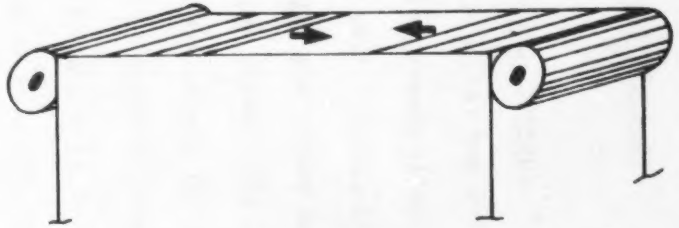
4.2.1 Controls for Interface Emissions

4.2.1.1 Covers. Covers are used on OTVC's to eliminate drafts within the freeboard and reduce diffusion losses. Covers can be manually operated, electrically powered (some powered models are automated to work with the cleaning cycle). Some typical covers are presented in Figure 4-1. Roll-top covers are typically plastic (mylar). In addition to roll-top covers, OTVC covers include flat covers made out of mylar or metal.

Manual covers are normally provided as standard equipment. These covers are intended to reduce OTVC emissions during idle time and periods of non-use (i.e., downtime). Manual covers should fit well and should be operated carefully to ensure that they do not become bent or otherwise damaged. If a lip exhaust is used, the cover should fit between the solvent vapor and the exhaust inlet. Manual covers can be flat-hinged, sliding, or roll-top. Hinged covers are not recommended because opening and closing these covers can disturb the vapor layer and unnecessarily expose the operator. If a flat-hinged cover moves too quickly, it can cause turbulence that can disturb the air/solvent vapor interface and increase emissions. Flat covers that slide horizontally off the machine reduce the disturbance to the vapor layer.



A. Roll Top Cover
(manual)



B. Bi-Parting Roll-Top Cover
(power)

Figure 4-1. Typical OTVC Covers

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To minimize disturbance of the air/solvent vapor interface, roll-top plastic (mylar) covers, canvas curtains, and guillotine (biparting) covers which close horizontally can be installed. Biparting covers can be made to close around the cables holding parts baskets when the basket is inside the cleaner. This affords complete enclosure during the cleaning phase. Powered biparting covers are usually operated by push button control with an automatic shut-off and are either pneumatically or electrically driven. The most advanced biparting covers are automated to coordinate cover movement with the movement of an automated parts handling system. This design minimizes the period of time the cover is opened, only allowing for part entry and exit from the cleaner. Powered biparting covers, which are closed during the cleaning cycle, reduce both idling and working losses due to diffusion by minimizing air drafts which disturb the air/solvent vapor interface. On larger machines, it is generally desirable to have powered (i.e., mechanically assisted) or automated covers.

Four tests were available for an automatic cover that was closed during most of the cleaner operation (Table 4-3, Tests 35, 36, 37, and 38). In these tests a biparting roll-top cover that was closed 79 percent of the time (275 seconds out of the 350 second OTVC cycle) was evaluated. Without the automated cover, working emission rates varied from 0.10 $lb/ft^2/hr$ (under calm air conditions) to 0.23 $lb/ft^2/hr$ (160 fpm room drafts). With an automated cover in use, working emission rates decreased to between 0.06 $lb/ft^2/hr$ (calm) to 0.11 $lb/ft^2/hr$ (160 fpm). This corresponds to working loss reductions of 38 percent (calm) to 53 percent (160 fpm). As expected, covers are more effective at higher air draft velocity. The effect of reduction of room drafts on emissions is discussed in Section 4.2.1.5.

4.2.1.2 Freeboard Refrigeration Devices. In all vapor cleaners, solvent vapor created within the machine is prevented from overflowing through use of primary condenser coils. Freeboard refrigeration devices consist of a second set of cooling coils located above the primary condenser coils of the cleaner. Functionally, the primary condenser coils define the upper limit of the vapor zone. The freeboard refrigeration coils chill the air immediately above the vapor zone forming a cool air blanket. The cool air blanket slows solvent diffusion and creates a temperature inversion zone within the freeboard which reduces the mixing of air and solvent vapors. Also, the cool air blanket supports lower solvent concentrations than warm air. Thus, some solvent at the interface between the solvent vapor zone and cool air blanket will condense into the cleaner. Freeboard refrigeration devices have proven to be an effective control for diffusional losses from an OTVC, although their effect is lessened if a cool primary condenser is present (see Section 4.2.1.3). A drawing of an OTVC equipped with a freeboard refrigeration device is presented in Figure 4-2.

There are two types of freeboard refrigeration devices, above-freezing and below-freezing. Above-freezing refrigerated freeboard devices operate at a temperature range around $5^{o}C$ ($41^{o}F$). Below-freezing refrigerated freeboard refrigeration devices operate with refrigerant temperatures usually in the range of -20 to $-30^{o}C$ ($-4^{o}F$ to $-22^{o}F$). Due to the low operating temperatures of the below-freezing units, provisions are made for a timed defrost cycle to melt the solvent/water ice that may form on the coils. If allowed to accumulate on the refrigerant coils, this ice layer would compromise heat transfer efficiency. The solvent/water mixture which

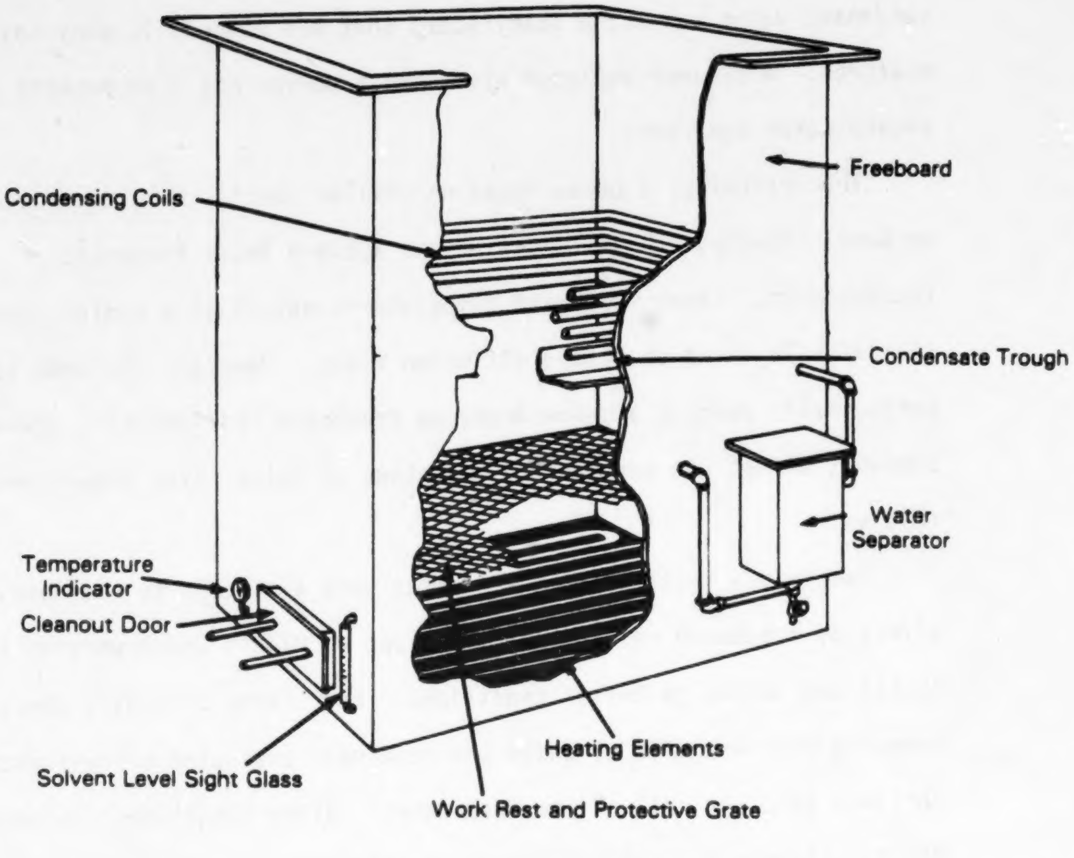
Freeboard
Condensing Coils
Condensate Trough
Water Separator
Temperature Indicator
Cleanout Door
Solvent Level Sight Glass
Heating Elements
Work Rest and Protective Grate
1682390R

Figure 4-2. Open Top Vapor Cleaner with Freeboard Refrigeration Device

is melted from the freeboard coils during the defrost cycle drains to a trough located below the freeboard refrigerator coils. To minimize water contamination of the solvent, the melted solvent/water mixture should be directed to a second water separator (distinct from the separator employed for the condensate from the primary condensing coils) for removal. Above-freezing freeboard refrigerated devices condense water from the air. The condensed water can strip stabilizers that are present in many solvent mixtures. A cleaner equipped with such a device may also benefit from a second water separator.

Theoretically, a below-freezing chiller should be more efficient than an above-freezing chiller since it can achieve lower freeboard temperatures. Lower freeboard temperatures establish a cooler, more stable inversion layer which lowers diffusion rates. However, the need to periodically defrost a below-freezing freeboard refrigeration device can somewhat offset the performance advantage of below- over above-freezing chillers.

Twenty-six tests from five sources were available to evaluate the effect of freeboard refrigeration devices on OTVC's under working (20 tests) and idling (6 tests) conditions. Four tests evaluated above-freezing chillers (AFC's) while the remainder evaluated below-freezing chillers (BFC's). All of the tests under idling conditions evaluated BFC's. Figures 4-3 and 4-4 summarize this data for idling and working conditions, respectively. Test numbers refer to the tests listed in Tables 4-1 and 4-3.

For working conditions, control efficiencies ranged from 18 to 50 percent for AFC (Tests 1 through 4). Three of the four AFC tests showed at least a 37 percent emission reduction. Under working conditions

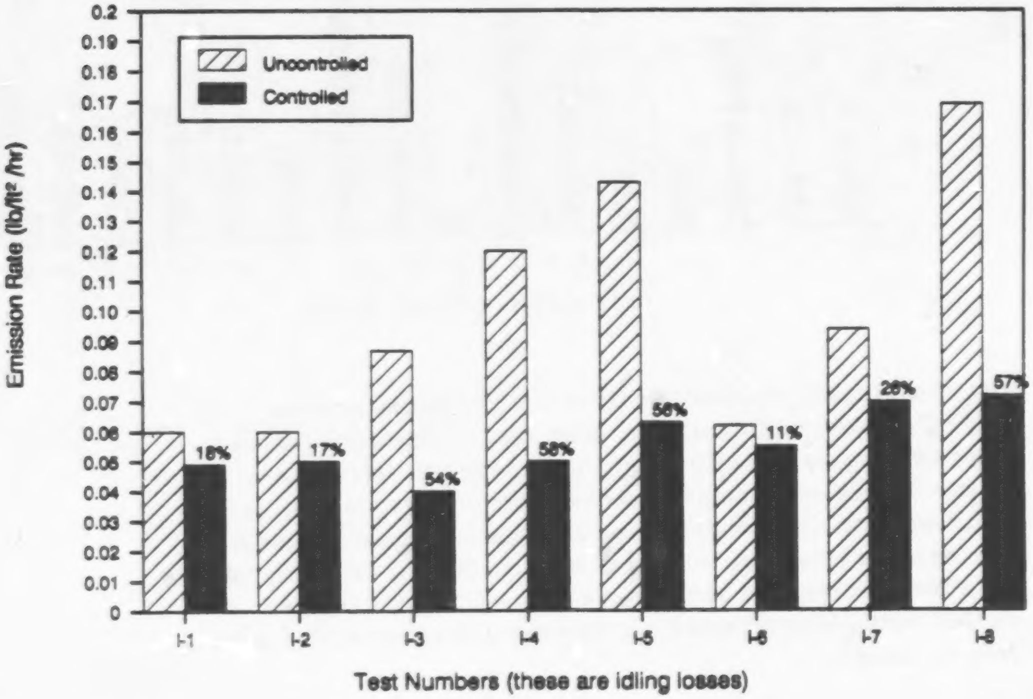

Figure 4-3. Freeboard Refrigeration Device Tests - Idling Conditions

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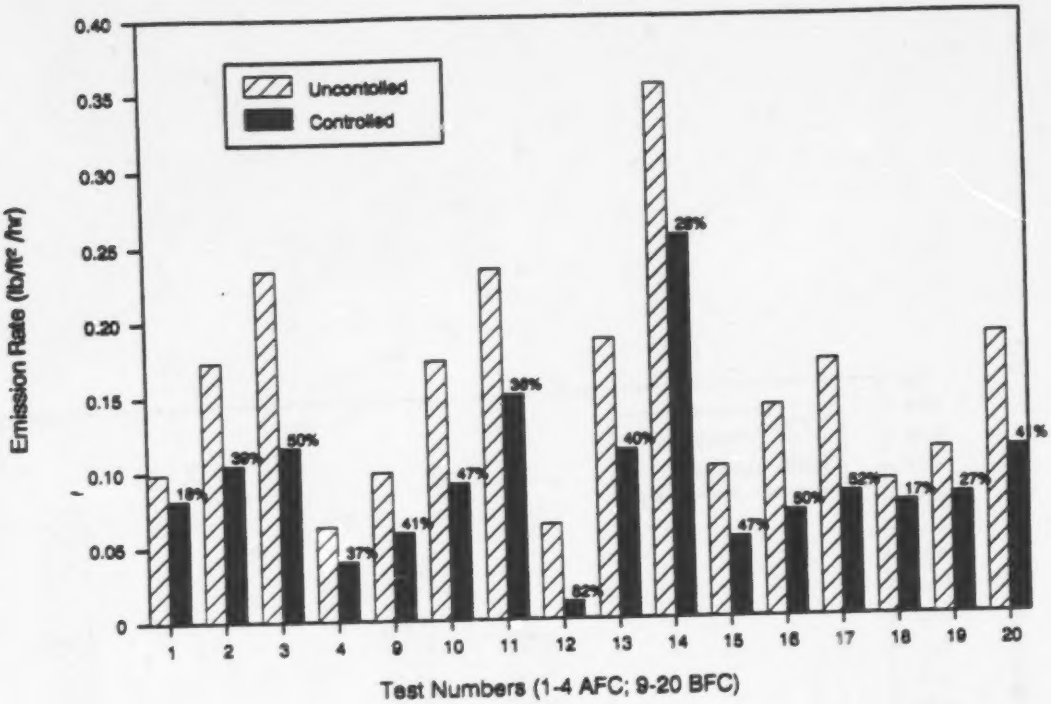

*Uncontrolled and controlled emission rates vary considerably under the "working" scenario, much more so than under idling conditions (see Figure 4-3., especially notice the low variability in the "controlled" data). This is to be expected because of the major impact on emissions from the workload. Tests performed by different companies reflect differing workload sizes, shapes, and cleaning cycles frequencies. A higher emission rate does not necessarily mean that a cleaner was less well controlled, but likely reflects the influence of a more demanding workload schedule or the cleaning of a workload more prone to carry out losses.

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Figure 4-4. Freeboard Refrigeration Device Tests - Working Conditions.*

(Tests 9 through 20), control efficiencies for BFC ranged from 28 to 82 percent. The observed 82 percent reduction (Test 12) should be considered atypical. Freeboard refrigeration devices primarily reduce diffusional losses. In a working OTVC, losses from solvent carryout on parts are significant and usually greater than diffusional losses, except where the machine is in a very drafty location. Therefore, in the more likely situation where workload related losses are significant or dominate, it would be impossible to achieve 82 percent emission reduction from a device designed to control diffusion losses. Controlled working emission rates for AFC ranged from 0.04 $lb/ft^2/hr$ to 0.12 $lb/ft^2/hr$. For BFC, controlled emission rates ranged from 0.01 $lb/ft^2/hr$ to 0.25 $lb/ft^2/hr$.

Efficiencies for BFC under idling conditions (Tests I-3 to I-8) ranged from 11 to 58 percent. Most notable in this series of tests is that the primary condensing temperature affects BFC effectiveness for CFC-113. As primary condensing temperature decreases, the additional benefit of a BFC also decreases. This effect is not nearly as pronounced with TCA. Primary condensation temperature is discussed further in the next section. Controlled idling emission rates with the use of a BFC ranged from 0.04 $lb/ft^2/hr$ to 0.07 $lb/ft^2/hr$.

The distance between the solvent vapor and secondary refrigerated freeboard coils has been reported to affect emission rate. An industry contact stated that this distance should be about 4 to 6 inches,[11] because convection patterns are unfavorable if the distance is outside this range. A test showed that increasing the separation from 5.5 inches to 7.5 inches increased losses by 17 percent. Another contact says the distance should not exceed 8 inches.[12] Still another contact stated that the freeboard refrigeration device should be within 4 inches of the top of the solvent cleaner, regardless of the distance from the primary condenser.[13] Available test data are insufficient to determine which distance is most effective.

Nonetheless, it is important that the freeboard refrigeration device be able to achieve a significant temperature inversion within the freeboard area (i.e., a temperature less than room temperature). Poorly designed freeboard refrigeration devices may not be able to establish the cooler temperatures at the center of the freeboard zone.

4.2.1.3 Refrigerated Primary Condenser. Although a primary condenser is standard equipment on all OTVC's, the temperature at which cooling is provided and the design of the coils and coolant flow have an effect on idling losses. Heat removal to balance the vapor generating heat input can be provided at various temperatures, through water, chilled water, or a direct expansion refrigerant. A lower temperature primary condenser, generally using a refrigerant as opposed to water, will lower diffusion losses. The likely reason for this effect is that colder primary condenser temperatures, besides condensing solvent vapor, also act to cool the air above the air/solvent vapor interface, somewhat like a freeboard refrigeration device. This will lower diffusion rates. The magnitude of this effect varies by solvent.

The relationships between emission rate and primary condenser temperature under idling and working conditions are presented in Figure 4-5, for two solvents: TCA and CFC-113 (Table 4-2; Tests 30 through 34). A steeper slope indicates a greater sensitivity to primary

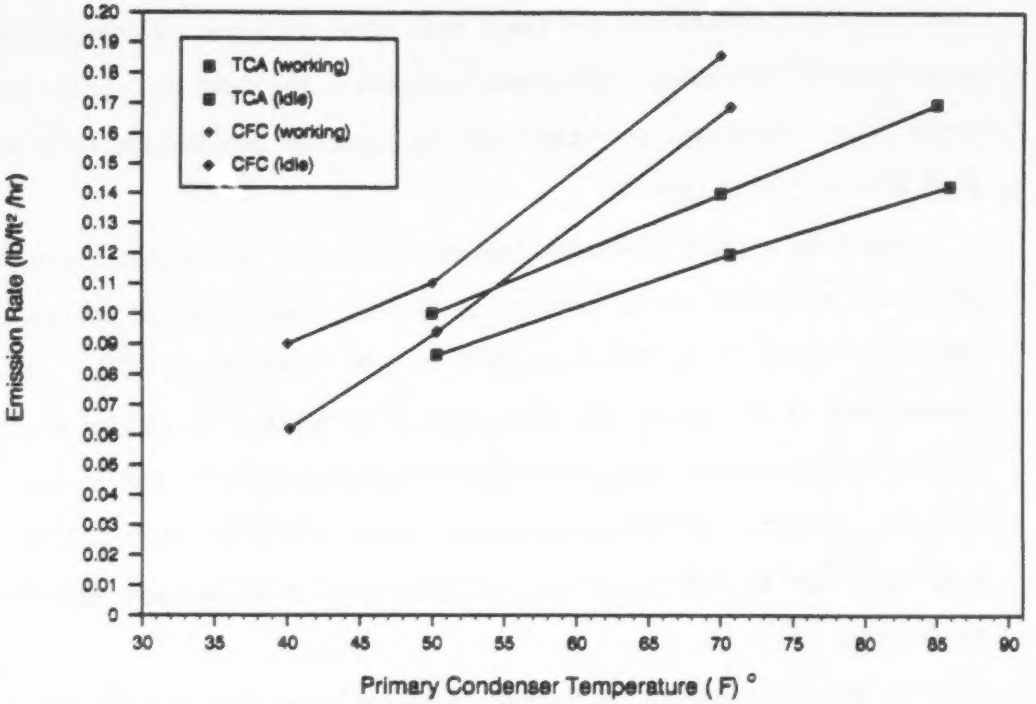

Figure 4-5. Effect of Primary Condenser Temperature on Uncontrolled Idle and Working Conditions

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condenser temperature. Uncontrolled working emissions for TCA ranged from 0.17 $lb/ft^2/hr$ at 85°F to 0.10 $lb/ft^2/hr$ at 50°F. Thus, a 41 percent reduction in working emissions of TCA can be obtained by reducing primary condenser temperature from 85°F to 50°F. For CFC-113, uncontrolled working emissions ranged from 0.19 $lb/ft^2/hr$ at 70°F to 0.09 $lb/ft^2/hr$ at 40°F. In the case of CFC-113, lowering the primary condenser temperature from 70°F to 40°F yields a 52 percent working emission reduction. It should be noted that "working" conditions for these test were simulated by introducing a water-cooled load using a programmable hoist. The load was cycled 12 times every hour. This type of setup would be expected to simulate relatively mild working conditions.

Reducing primary condenser temperature during idling has a similar effect on emissions as for working conditions. Uncontrolled emissions for TCA range from 0.14 $lb/ft^2/hr$ at 85°F to 0.09 $lb/ft^2/hr$ at 50°F. This corresponds to an idling loss reduction of 39 percent associated with decreasing the primary condenser temperature from 85°F to 50°F. For CFC-113, uncontrolled idling emissions ranged from 0.17 $lb/ft^2/hr$ to 0.06 $lb/ft^2/hr$ at 40°F, or a control efficiency of 63 percent under idling conditions.

It is unlikely that all solvent cleaners using TCA and CFC-113 will operate their primary condensers at 85°F and 70°F, respectively. In fact, for CFC-113 machines, primary condensation usually is accomplished through direct expansion refrigeration or chilled water systems operating at 40 - 60°F. However, even if primary condenser temperatures for TCA and CFC-113 are at 70°F and 50°F, respectively, additional diffusion reduction can still be obtained. Referring to Figure 4-5, the tests show that lowering the primary condenser temperature for TCA from 70^0F to 50^0F reduces working emissions from 0.14 $lb/ft^2/hr$ to 0.10 $lb/ft^2/hr$; this corresponds to a 29 percent reduction. Similarly, reducing the primary condenser temperature on a CFC-113 machine from 50^0F to 40^0F will reduce working emissions from 0.11 $lb/ft^2/hr$ to 0.09 $lb/ft^2/hr$, an 18 percent reduction.

These tests also examined the effect of the addition of a below-freezing freeboard refrigeration device onto a machine operating with a refrigerated primary condenser. For cleaners using TCA, the addition of a freeboard refrigeration device to a cleaner with a primary condenser at 50^0F still has a significant effect on emissions, reducing emissions by more than 50 percent. Very little reduction was obtained by adding a freeboard refrigeration device to a CFC-113 machine operating at a primary condenser temperature of 40^0F.

One drawback to lowering primary condenser temperature is that it promotes condensation of ambient water vapor, especially in humid climates. Therefore, it is imperative that machines employing low temperature condensation contain adequately sized water separators or dessicant dryers to minimize water contamination.

The test results on primary condenser temperatures suggest another area of concern for water-cooled OTVC's. Machines using tap water, cooling tower water, or well water will be subject to seasonal temperature variations. During summer months condenser water temperatures may rise significantly and may cause undesirable diffusion loss increases. This effect may be exacerbated by increased ambient drafts from open doors and windows in warm weather. Use of chilling or refrigerant systems to control condensing temperatures will minimize seasonal variations.

4.2.1.4 Increased Freeboard Ratio. The freeboard height on an OTVC is the distance from the the air/solvent vapor interface to the top of the tank walls. The freeboard zone serves to reduce air/solvent vapor interface disturbances caused by room drafts and provides a column through which diffusing solvent molecules must migrate before escaping into the ambient air. Higher freeboards reduce diffusional losses by diminishing the effects of air currents and lengthening the diffusion column. An OTVC with an increased freeboard is presented in Figure 4-6.

In discussing the adequacy of freeboard height to reduce solvent loss, it is common to refer to the freeboard ratio. The freeboard ratio is the freeboard height divided by the interior width of the solvent cleaner. The freeboard height should be measured from the established air/solvent vapor interface to the top of cleaner walls or to the bottom of any opening in the cleaner walls. Freeboard width is the inside width of cleaner walls or, if irregular, the largest width dimension of the air/solvent vapor interface directly exposed to the atmosphere. The freeboard ratio is used in recognition of the fact that as cleaner width increases, susceptibility to the adverse influence of drafts increases unless the freeboard height is proportionally increased to compensate for the increasing machine width. Two cleaners of differing size (width) but with identical freeboard ratios roughly are equally protected from drafts.

A high freeboard on some machines may make it difficult for an operator to easily lower parts into the machine, unless an elevated work platform is installed. However, as discussed in Section 4.2.2.1, a hoist

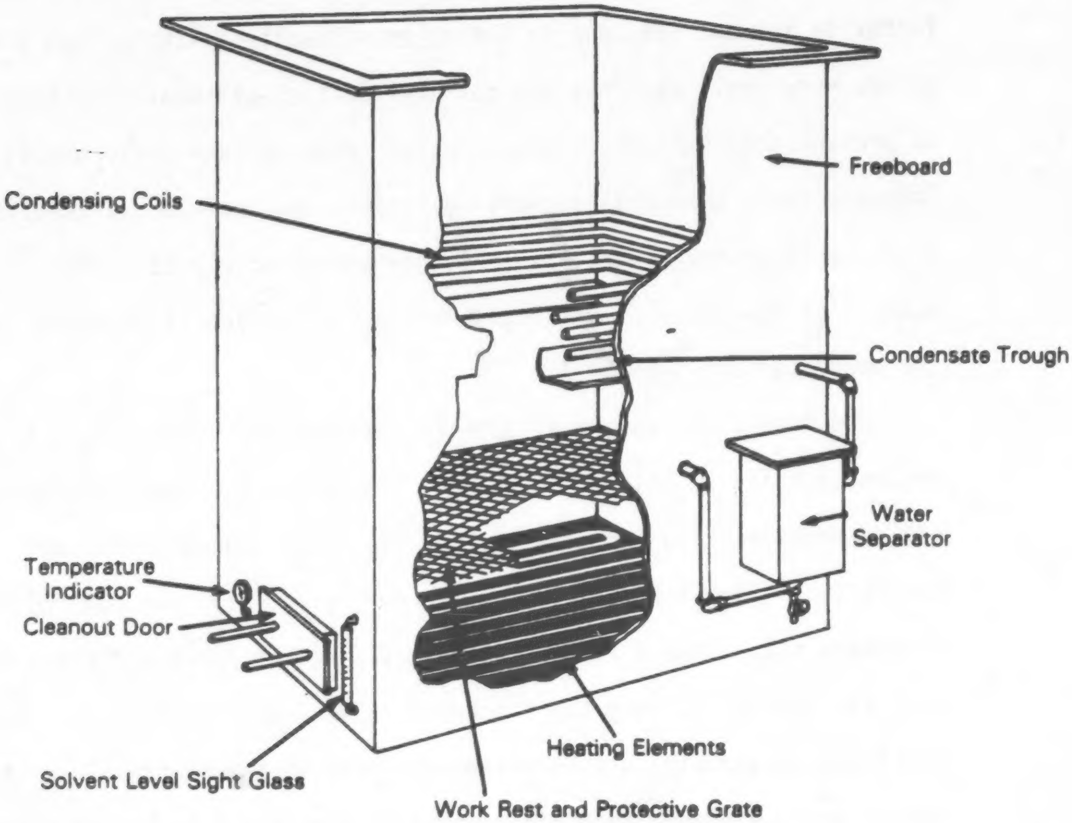
Freeboard
Condensing Coils
Condensate Trough
Water Separator
Temperature Indicator
Cleanout Door
Heating Elements
Solvent Level Sight Glass
Work Rest and Protective Grate
1682390R

Figure 4-6. Open Top Vapor Cleaner with Increased Freeboard

can be used on large machines to overcome the problem of machine height and reduce workload related losses. On very large machines, raised freeboards may be so tall as to restrict the ability to place parts in the machine. For these situations, slightly lower freeboards might be necessary, but special care should be taken to minimize room drafts.

For small OTVC sizes, the absolute freeboard height is an important factor in solvent loss due to diffusion. Despite having a high freeboard ratio, very small machines may not have sufficient total freeboard height to prevent accelerated diffusion losses, even in calm environments. Industry tests show that solvent loss rates can increase substantially with absolute freeboard heights of less than approximately 12 inches.[14] An example of how emission rates can vary as a function of freeboard height are presented in Figure 4-7.

Fourteen tests were available to evaluate the effect of an increased freeboard ratio on solvent emissions. Twelve of the tests evaluated this effect under working conditions while two tests evaluated idling conditions. Emission reductions were evaluated for: (a) raising the freeboard ratio from 0.75 to 1.0, (b) raising the freeboard ratio from 1.0 to 1.25, and (c) raising the freeboard ratio from 0.75 to 1.25. As mentioned previously, a 0.75 freeboard ratio is representative of baseline conditions. Although some older machines may have 0.5 freeboard ratio, most vendors currently sell OTVC with freeboard ratios of at least 0.75.

The available data on the effect of an increased freeboard ratio are presented in Table 4-1 (Tests I-19 and I-20) and Table 4-2 (Tests 47 through 58) for idling and working conditions, respectively. The data for working conditions are presented graphically in Figure 4-8.

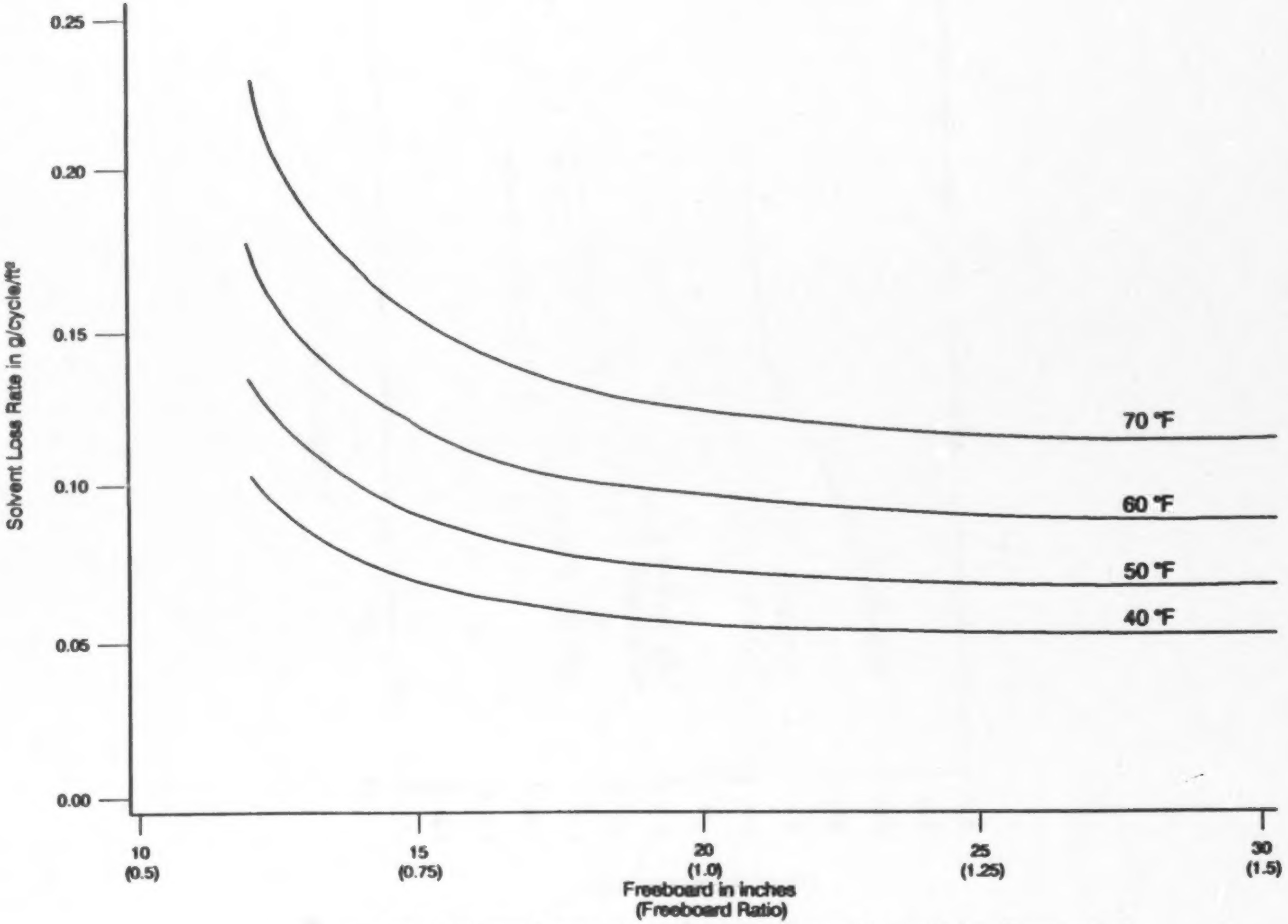

Figure 4-7. Solvent loss rate versus freeboard height for Genesolv® D under Idle conditions

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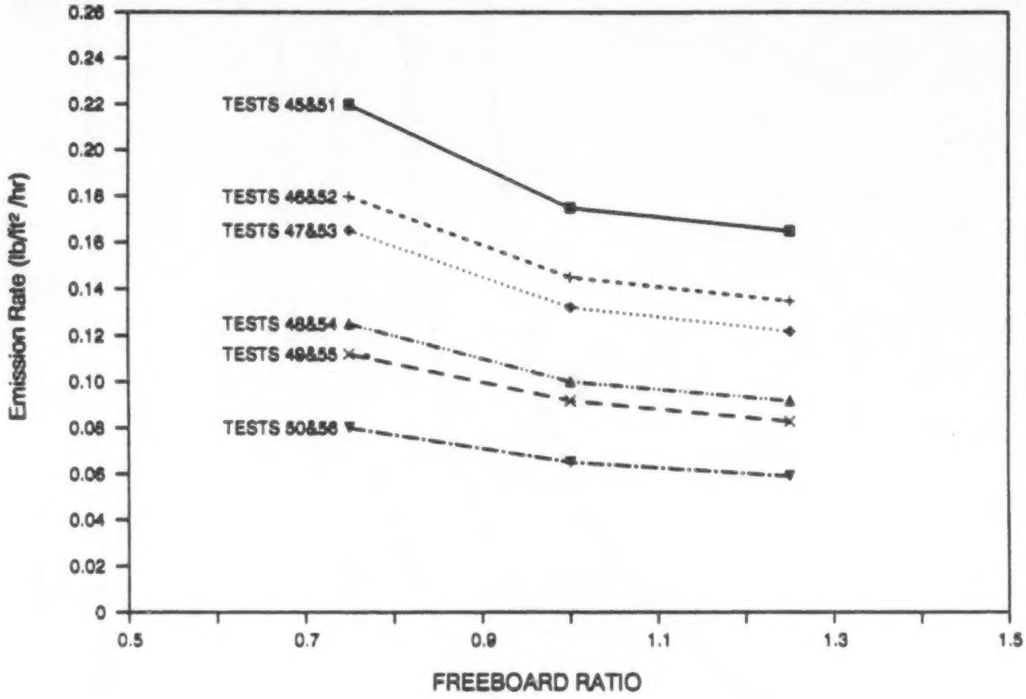

Figure 4-8. Effect of Freeboard Ratio - Working Conditions: 6 OTVD Tests

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Under working conditions, the control efficiencies associated with raising the freeboard ratio from 0.75 to 1.0 ranged from 19 to 21 percent. Controlled emission rates at a freeboard ratio of 1.0 ranged from 0.06 $lb/ft^2/hr$ to 0.18 $lb/ft^2/hr$. The control efficiencies associated with raising the freeboard ratio from 1.0 to 1.25 ranged from 6 to 10 percent. The controlled emission rates at a freeboard ratio of 1.25 ranged from 0.06 $lb/ft^2/hr$ to 0.16 lb/ft^2 hr. Using the above data, the efficiencies associated with raising the freeboard ratio from 0.75 to 1.25 are calculated to be approximately 25 percent.

For idling conditions, data are available to evaluate the effect of raising the FBR from 0.75 to 1.0. No data are available for estimating the efficiencies of an increased freeboard ratio to 1.25 under idling conditions. Under idling conditions, the control efficiencies associated with raising the freeboard ratio from 0.75 to 1.0 were -6 and 39 percent, based on two tests. The test with a negative efficiency was conducted under calm air conditions. Therefore, the expected reduction in emissions would be lower than for tests conducted under higher air speed conditions. However, the negative efficiency result can likely be attributed to measurement inaccuracies. In fact, measured losses for uncontrolled and controlled scenarios were very small and could be considered the same, within experimental precision.

Another strategy related to raising the freeboard for emission control is the design of narrower cleaners. For the same air/solvent vapor interface area, a square interface configuration is more susceptible to room drafts than a long narrow rectangular configuration, especially if the cleaner can be oriented in the room so that any drafts blow across the narrower dimension.

4.2.1.5 Reduced Room Draft/Lip Exhaust Velocities. Air movement over an OTVC affects the solvent emission rate by sweeping away solvent vapors diffused into the freeboard area and creating turbulence in the freeboard area which will enhance solvent diffusion as well as solvent vapor and air mixing.

In industrial manufacturing settings, solvent cleaners often are operating in high draft areas, typically in excess of 130 fpm.[15] Reducing room drafts to calm conditions (30 fpm or less) can greatly reduce emission rates. The available data for evaluating the effect of reduced room draft velocity are under working conditions (see Figure 4-9). These data are from tests showing the effects of draft velocity on emissions at a constant 0.75 freeboard ratio (Table 4-3, Tests 59, 60). The emission rates from the tests are 0.23 $lb/ft^2/hr$ at 160 fpm, 0.17 $lb/ft^2/hr$ at 130 fpm, and 0.1 $lb/ft^2/hr$ at calm conditions. Reducing room drafts to calm conditions corresponds to a 43 percent reduction from working emissions with room drafts of 130 fpm and a 58 percent reduction from working emissions at 160 fpm.

A lip exhaust, described in Chapter 3, affects emissions much like air speed; it increases mixing and diffusion in the vapor layer. Tests have shown that a lip exhaust, even when properly operated, can double solvent consumption.[16] If the solvent is not recovered through the use of a carbon adsorber, overall emissions will increase.

Tests have been conducted on the effect of turning off a lip exhaust on both idling and working conditions (Table 4-2, Tests I-16, I-17, and I-18 and Table 4-3, Tests 27, 28, and 29, respectively). The lip exhaust

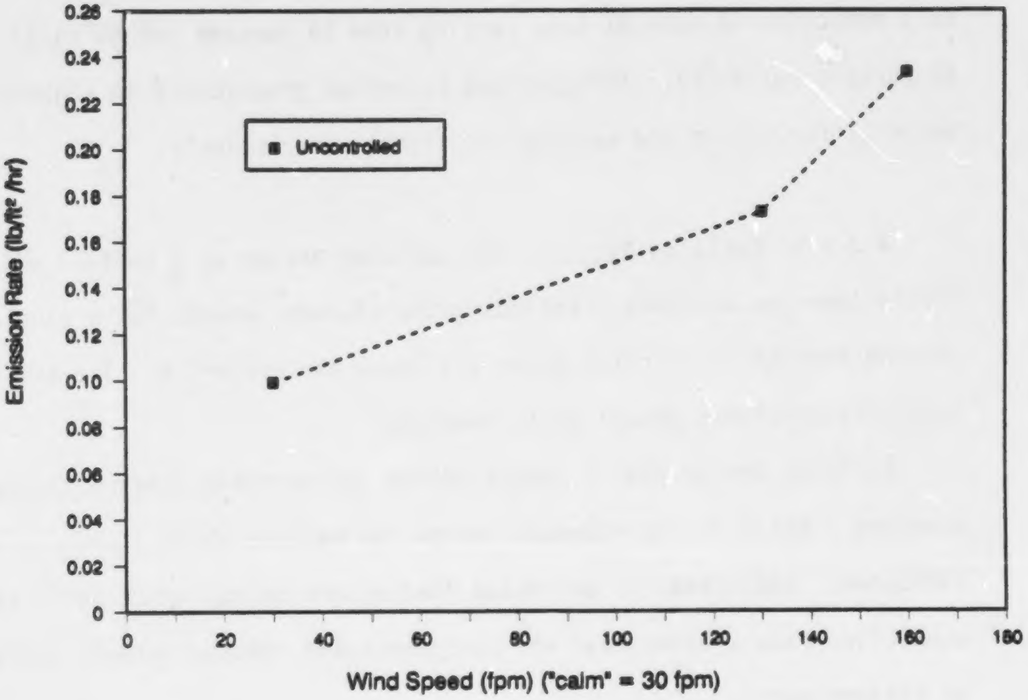

Figure 4-9. Effect of Wind Speed

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was operated at the rate of 90 ft^3/min per ft^2 of cleaner area; this corresponds to 900 ft^3/min for this particular test. Based on test data for working conditions, the emission rates encountered with a lip exhaust system in operation ranged from 0.22 $lb/ft^2/hr$ (with primary condenser temperature of 50^oF) to 0.28 $lb/ft^2/hr$ (with primary condenser temperature of 85^oF). With the lip exhaust turned off, the emission rates decreased to 0.10 $lb/ft^2/hr$ (at 50^oF) and 0.16 $lb/ft^2/hr$ (at 85^oF). This corresponds to a reduction in solvent loss ranging from 54 percent (at 50^oF) to 42 percent (at 85^oF). The data are presented graphically in Figures 4-10 and 4-11 for idling and working conditions, respectively.

4.2.1.6 Enclosed Design. The enclosed design as a control option for OTVC's involves completely enclosing the cleaner, except for a single opening through which parts enter and leave the enclosure. The enclosure typically precludes manual parts-handling.

Enclosed design OTVC's reduce idling and workload related losses by creating a still air environment inside the machine which limits solvent diffusion. Additionally, automated loading and unloading of parts at a controlled rate creates less air turbulence and reduces solvent carry-out on cleaned parts.

Schematics of two variations of enclosed designs are shown in Figure 4-12. The enclosed design with a horizontal entry/exit port (Figure 4-12.A) is not affected by room air drafts. This design does not require a port cover during machine operation. The enclosed design with a

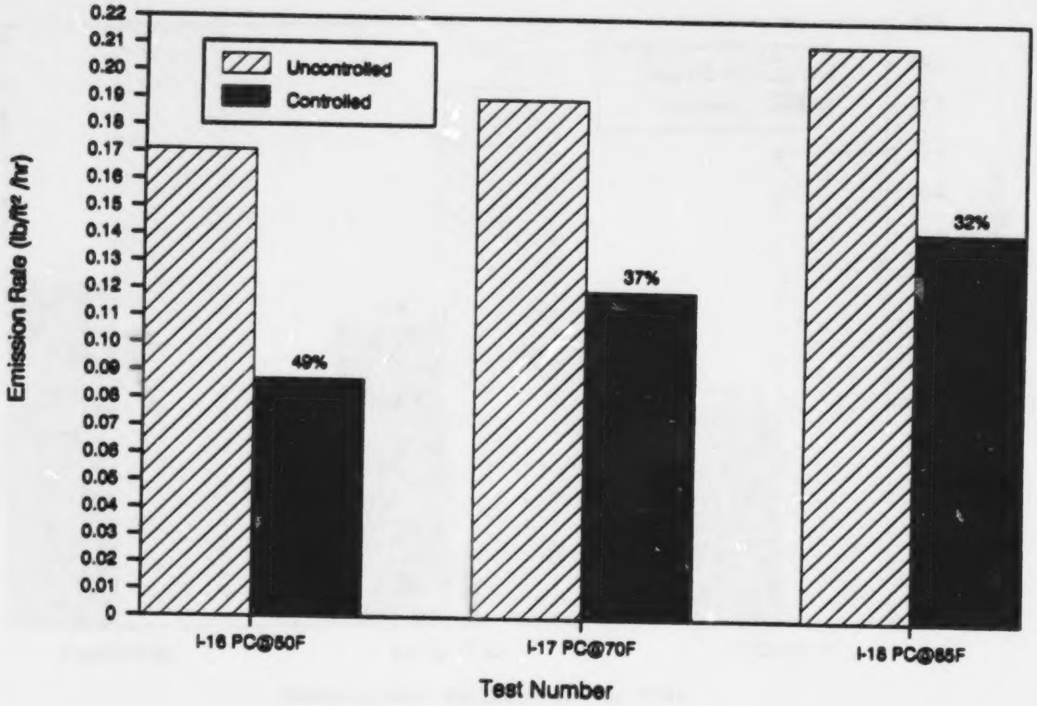

Figure 4-10. Lip Exhaust Effects - Idling Conditions

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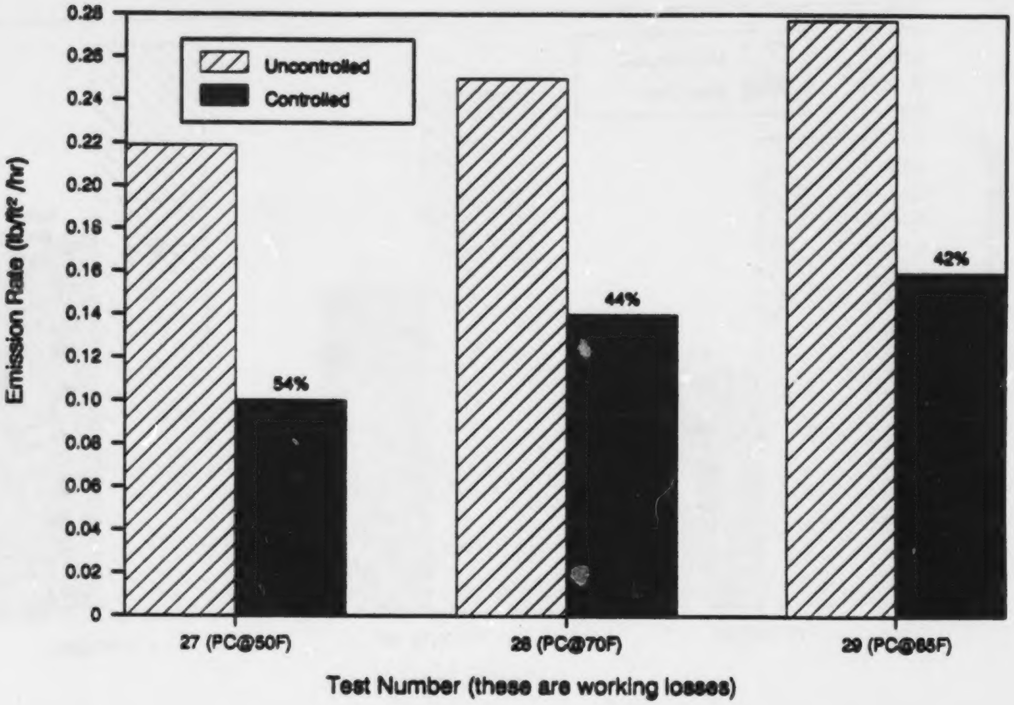

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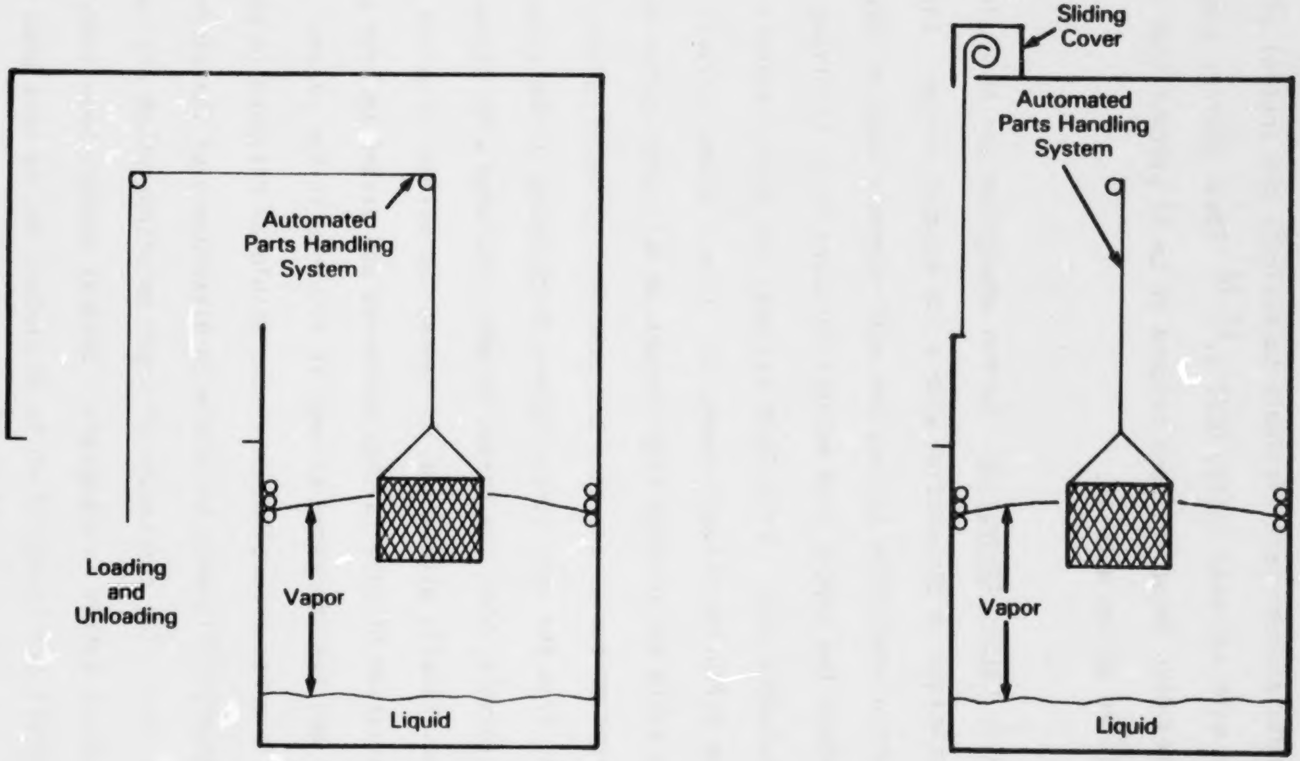
Figure 4-11. Lip Exhaust Effects - Working Conditions


Sliding Cover
Automated Parts Handling System
Automated Parts Handling System
Loading and Unloading
Vapor
Liquid
Vapor
Liquid
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A. Horizontal Port

B. Vertical Port (with cover)

Figure 4-12. Enclosed Open Top Vapor Cleaners

vertical entry and exit port should have a sliding door that will be closed except when parts are being loaded or unloaded.

Two data sources were available to evaluate the control efficiency associated with enclosed design OTVC's.[17,18] These sources showed that uncontrolled OTVC emissions were reduced 42 to 67 percent upon conversion to an enclosed design machine.

4.2.1.7 Carbon Adsorption. Carbon adsorption can be employed as a control technique in conjunction with a lip exhaust system. Lip exhaust/carbon adsorption systems are most commonly used on large solvent cleaners where the credit from solvent recovery helps to offset the high capital equipment cost. With these systems, peripheral exhaust ducts capture the diffusing solvent vapors and to some extent solvent evaporating from clean parts and directs them through an activated carbon bed. The solvent vapor molecules are adsorbed onto the activated carbon, removing the solvent from the vent stream before discharging to the atmosphere.

At intervals, when the carbon becomes saturated with solvent, the bed is desorbed, usually with steam, to remove the solvent from the carbon. The solvent/steam mixture is then condensed and passed through a water separator, and the recovered solvent is returned to the cleaner.

The lip exhaust ventilation system should be designed to maximize solvent capture efficiency and minimize disturbance of the air/solvent vapor interface. The percentage of vapor emissions which are captured by the lip exhaust system is uncertain. Several vendors have indicated a lip exhaust capture efficiency of 40 to 99 percent but no test data were provided for justification.[19,20,21]

Proper operation and maintenance procedures are critical to maintain the control efficiency of carbon adsorption systems. Examples of operating procedures which have a negative impact on control efficiency include: (1) dampers which do not open and close properly, allowing solvent-laden air to by-pass the carbon beds; (2) use of carbon that does not meet specifications, and (3) improper timing of the desorption cycles. Desorption cycles must be frequent enough to prevent breakthrough of the carbon beds, but not so frequent to cause excessive energy consumption. Carbon adsorbers should not be by-passed during the desorption process. A dual bed design can be used so that while one bed is being desorbed, solvent emissions can be routed to the second bed.

One test was available to evaluate the efficiency of carbon adsorbers for controlling solvent emissions.[22] This test indicated that a lip exhaust/carbon adsorber system could control solvent emissions by 65 percent. However, the test report did not specify whether the baseline emission rate included lip exhaust. If the baseline OTVC did have a lip exhaust, the 65 percent emission reduction overstates the achievable reduction for a carbon adsorber and lip exhaust installed on an OTVC without a lip exhaust. Thus, there is some uncertainty in the validity of this data point. Another source indicated that the overall effect of installing a lip exhaust/carbon adsorber system on an OTVC would be a 40 percent reduction in total emissions.[23] Because of the emission increase associated with adding a lip-exhaust, the overall effectiveness of control using carbon adsorption for OTVC's is likely closer to 40 percent than 65 percent.

Depending upon the solvent mixture and the type of objects being cleaned, adverse effects may be encountered with carbon adsorption. Where solvent mixtures or stabilizers are used, the solvent vapor collected by the exhaust system may be richer in the more volatile components, and the recovered solvent mixture will not be identical to the fresh solvent. Also, some stabilizers or cosolvents used in solvent mixtures are water soluble. After desorption, the steam used to desorb solvent and stabilizers from the carbon bed is condensed. The water soluble components remain in the water and are lost, unless recovered by distillation. Many users are not willing or able to undertake tasks such as analysis and reformulation of the solvent, and handling toxic or flammable stabilizers.

In addition, by-products of uncontrolled solvent degradation, such as hydrochloric acid, can be corrosive to the adsorption equipment and/or hazardous to operators. For some solvents or cleaning applications, it may be necessary to use special materials of construction for the adsorber, such as stainless steel or other alloys, or take other measures to prevent potential problems which could lead to solvent degradation and damage to the equipment. One solvent in particular, TCA, is troublesome when used in carbon adsorption. It is heavily stabilized and many of the stabilizers may be removed during carbon adsorption, causing solvent breakdown and equipment corrosion. Carbon adsorption probably should not be attempted with this solvent at this time. However, recent studies indicate that carbon adsorption systems for use with TCA will be available in the future.[24]

4.2.2 Controls for Workload Emissions

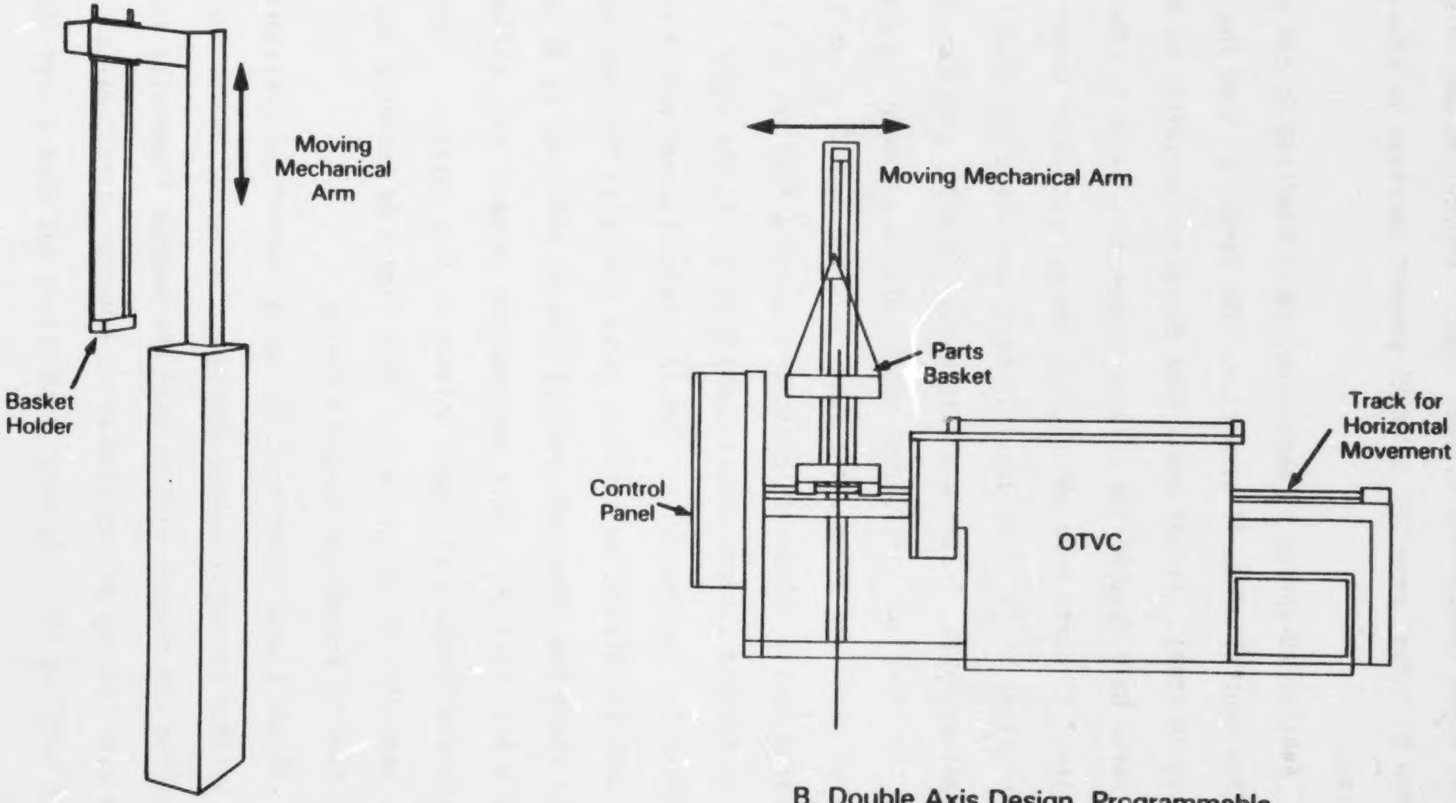
4.2.2.1 Mechanically Assisted Parts Handling/Parts Movement Speed. The method employed for moving parts through the OTVC cleaning cycle has a direct effect on the magnitude of workload related emissions. Rapid movement of parts will increase solvent loss due to carry-out of liquid solvent and entrainment of solvent vapor, and increased disturbance at the solvent/air interface. As mentioned in Chapter 3, workload losses are a large portion of total working losses (see Chapter 3 for additional discussion of workload related losses).

Parts can be moved through the cleaning cycle either by a human operator or through the use of a mechanical system. A human operator is generally unable to move parts at or below the maximum speed of 11 feet per minute (fpm), as required in many State regulations and recommended in EPA guidelines.[25,26,27] According to one vendor, it is difficult to maintain a constant speed if a full basket weighs around 10 pounds or more (baskets can weigh in excess of 50 pounds).[28,29] Operator training may have limited success in lowering the basket movement rate. However, the speed of the basket is difficult to judge, and operators will typically return to faster rates, especially if the load is heavy enough to cause fatigue toward the end of the workday.[30] In some industries, operators are paid on a per-piece basis. This may be further incentive to move parts more quickly.[31] Industry estimates of parts movement by typical human operators are in excess of 60 fpm.[32,33] At these speeds, the working losses would be much higher, perhaps by several times, than the data presented in Chapter 3 for working losses (reflecting use of hoists). Use of a mechanical parts handling system can reduce emissions by consistently moving parts into and out of the machine at appropriate rates, thereby eliminating excess losses caused by manual operation. A parts handling system can be operated by push button, or can be automatic and programmable. Two typical parts handling systems are shown in Figure 4-13. The first is a single axis hoist that can be operated by a push button, whereas the second is a double axis programmable parts handling system.

Although the emission reduction benefit of using mechanically assisted parts handling is generally not disputed, there are few data available to characterize the magnitude of the benefit.

One test is available that simulates the effect of switching from a human operator to a system (Table 4-3, Test 26). The test compared a hoist operated at 20 fpm (to simulate a human operator) to a hoist operated at 10 fpm. The lower speed was found to reduce working losses by 28 percent. Since human operator speeds are generally higher than 20 fpm, the reduction attributable to the use of a hoist is likely larger than 28 percent.

There has been some concern whether even the present 11 fpm limit is too high. At 11 fpm, substantial disturbance of the air/ solvent vapor interface still occurs.[34,35] Further, lowering the hoist speed can allow parts to dry more thoroughly prior to removal and create less air turbulence during part entry and exit from the cleaner. Therefore, working losses due to solvent carryout and diffusion are minimized. One manufacturer has evaluated the effectiveness of reducing hoist speed further, particularly as the parts basket moves through the solvent vapor layer (Table 4-3, Test 25). During the test, a variable speed, programmable hoist was used to lower the hoist speed to 3 fpm as the parts


Moving
Mechanical
Arm
Basket
Holder
Moving Mechanical Arm
Parts
Basket
Control
Panel
OTVC
Track for
Horizontal
Movement

A. Single Axis Design

B. Double Axis Design, Programmable

Figure 4-13. Automated Parts Handling System

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basket moved through the solvent vapor. Decreasing the hoist speed from 11 fpm to 3 fpm, resulted in an 81 percent decrease in total working losses.

Another advantage of mechanical parts handling is the potential for precise control of dwell time (i.e., the length of time the part remains in the vapor zone). Proper dwell time decreases emissions by ensuring that the parts have reached the solvent temperature prior to removal from the machine. If parts have not reached the solvent vapor temperature, condensation would still occur as parts are withdrawn from the machine and solvent carry-out losses would increase. A hoist can also be made to pause slightly above the air/solvent vapor interface within the freeboard area as cleaned parts are being withdrawn. This reduces carry-out losses by allowing pooled solvent to drain or evaporate from the parts with much of the evaporated solvent either sinking back into the vapor zone or being condensed on cooling coils. One test measuring the effect of pausing in the cold air blanket on emission rates indicated that adding a two-minute dwell above the vapor zone reduced working emissions by 46 percent (Table 4-3, Test 24). This test was run on parts that collected substantial amounts of liquid solvent on flat surfaces. Other types of workloads that do not collect as much liquid on surfaces would not need as much time to accomplish adequate drying.

An additional benefit of the use of mechanical transport systems is the ability to reduce worker exposure. In manual operations, a person operating the cleaner will be near the machine frequently and may have to bend over the top of the cleaner to lower or extract parts. Mechanical parts handling not only reduces emissions but also allows the operator to work farther away from the cleaner. This has become especially important since OSHA has lowered the permissible exposure limit (PEL) for PCE to 25 ppm for an eight-hour period and to 50 ppm for TCE and is expected to lower the PEL for MC in the near future.

In order to minimize working losses, mechanically assisted parts handling should be employed while parts are within the solvent vapor, air/solvent vapor interface, or freeboard area. Parts on which liquid solvent has pooled or otherwise been trapped should remain in the freeboard area just above the air/solvent vapor interface until the liquid solvent has completely evaporated. Also, parts baskets should be suspended from metal chain or cables, not from fiber rope (or any porous material) which can absorb solvent.

4.2.2.2 Hot Vapor Recycle/Superheated Vapor. Another means of dramatically reducing carry out of solvent on cleaned parts is by employing hot vapor recycle or superheated vapor technology. These two technologies aim to create zones of superheated solvent vapor within the vapor layer. Cleaned parts are slowly passed through a superheated zone, warming the parts and evaporating liquid solvent on parts surfaces before they are withdrawn from the cleaner. Solvent vapors heated to approximately 1.5 times the solvent boiling point are used.[36] Hot vapor recycle and superheated vapor technologies are relatively new and predominantly used in conveyorized cleaners, although development work is continuing on OTVC. Further discussion of these control techniques and their effectiveness is contained in Section 4.3.2.3.

4.2.3 Proper Operating and Maintenance Practices

Proper operating and maintenance practices are critical to keeping solvent emissions at a minimal level; neglect can lead to major sources of emissions. The discussion below recommends practices that will limit solvent loss due to operating and maintenance activities. No effort was made to quantify the solvent loss reduction associated with these good operating and maintenance practices because effectiveness varies widely, depending on current practices.

Reducing Drafts. Emissions due to diffusion and convection can be reduced by covering the OTVC when parts are not being cleaned and by reducing room drafts, such as through the use of baffles or by reducing room ventilation flow rate near the solvent cleaner.

Spray Techniques. For OTVC's equipped with spray cleaning systems, spraying within the vapor zone and at a downward angle helps to control excess solvent loss. Such a practice reduces liquid solvent forced out of the OTVC and minimizes turbulence which can increase diffusion losses. Machines equipped with permanently mounted spray nozzles eliminate the possibility of spraying outside the vapor zone. With the common use of ultrasonics to enhance cleaning, the need for solvent sprays on many OTVC is minimal and could be eliminated.

Allied Corporation tested the effects of spraying location on solvent loss rates. The data is presented in Table 4-4 for two primary condenser temperatures. The test data show that it is important to spray parts well below the vapor line. Solvent losses with spraying 5 inches above the vapor line are 10 times higher than losses with spraying 4 inches below the vapor line. These tests were conducted using a cleaner with a 24 inch freeboard and ten 40-second spraying cycles per hour.

Startup/Shutdown Procedures. A proper start-up practice that reduces solvent emissions involves starting the condenser coolant flow prior to turning on the sump heater. This practice helps condense solvent from the saturated zone above the liquid solvent before the air is forced out of the machine as solvent vapors rise. Conversely, a good shut-down practice involves allowing the condenser to stay on after the sump heater has been turned off, until the vapor layer collapses. Solvent cleaners that operate on a heat pump design cannot accommodate independent control of heating and cooling, since heat input and condensation are part of the same thermodynamic cycle.

Downtime Losses. Solvent evaporation during downtime can be significant, especially so for CFC-113, and methylene chloride. Use of covers during downtime will reduce drafts and slow diffusion, but will not stop losses completely. Several techniques can be used to reduce downtime losses including operating a freeboard refrigeration device, using a sump cooler to reduce solvent vapor pressure, and pumping solvent out of the machine to an airtight storage drum. Among these techniques, cooling the sump during downtime is reportedly very effective at reducing the solvent losses due to evaporation. Sump cooling can be accomplished by two methods: 1) the liquid solvent can be cooled during downtime by cooling coils, or 2) the air blanket directly above the liquid solvent can be cooled by an overlay coil. One vendor indicated that cooling the sump can reduce downtime losses by 90 percent.[37]

TABLE 4-4. SOLVENT LOSS RATE VERSUS SPRAYING PRACTICES (LB/FT^2/HR) TEN 40 SECOND CYCLES PER HOUR GENESOLV D, 24 INCH FREEBOARD

	50° Cooling Water		70° Cooling Water	
	Loss	%	Loss	%
No Spray	0.0565	0	0.0837	0
4" Below Vapor	0.0742	31	0.1173	40
5" Above Vapor	0.2135	278	0.3010	260
10" Above Vapor	0.5448	864	0.9484	1033

Source: Reference 10

Workload Introduction/Removal. Emissions due to the entry and removal of parts can be reduced with good operating practices. One such practice is limiting the rate of introduction of the workload in order to minimize the turbulence created when the load is lowered into the cleaner. Limiting the rate of introduction of the load so that the air/solvent vapor interface does not fall more than a few inches will prevent excessive pump out of mixed solvent vapor and air as the vapor layer reestablishes. As stated previously, the use of mechanical parts movers can substantially eliminate these emissions. Emissions can also be reduced by limiting the horizontal area of the load to be cleaned to 50 percent or less of the OTVC air/solvent vapor interface area. This will mitigate the displacement and turbulence of solvent vapors as the load is lowered into the cleaner. However, larger parts baskets could be used without increasing emissions if the basket speed were reduced when the basket moved through the vapor zone.

Parts Drainage. An important operating practice that minimizes solvent carry-out on cleaned parts is proper racking to avoid solvent puddles if possible. Parts with recesses or blind holes should be rotated or agitated prior to removal from the vapor layer to displace trapped solvent. Powered rotating baskets (discussed in 4.3.2.2) can also be used to limit liquid carry-out effectively. The cleaning of porous or absorbent materials, which will carry out excessive quantities of solvent, must be avoided. Also, the part being cleaned should be allowed to reach the solvent vapor temperature prior to removal from the vapor layer, so that solvent condensation on the part no longer occurs.

Leak Detection/Repair. Solvent emissions can also be controlled by repairing visible leaks and repairing or replacing cracked gaskets, malfunctioning pumps, water separators, and steam traps promptly. Routine equipment inspections will help locate leaks or problem areas more quickly. Halide detectors that can be used to identify leaks are available at a reasonable cost ($150 to $500).

Leaks at welded joints can be avoided if the OTVC vendor tests the joints prior to shipping. The test must be sensitive enough to detect fine cracks. A simple water test is not sufficient because high surface tension of water prevents penetration of small cracks. Often a dye penetrant is used. Machines made with 316L stainless steel walls will be less prone to stress cracks. Pressure fittings, as opposed to threaded connections, have also been reported to reduce leaks.[38]

Clean out doors, viewing ports, or other gasketed machine parts must be carefully designed and manufactured. Gasket material must be nonporous and resistant to chemical attack of the solvents used. Ill-fitting gaskets or use of improper gasketing material can result in large solvent losses.

Solvent Transfer. Losses during transfer of solvent into and out of the OTVC can be controlled by correct operating practices. Ideally, solvent filling, draining, and transfer operations should be by pipe in closed systems. Some vendors have systems that allow for pumping solvent from the solvent drum directly into the solvent cleaner.[39] This could cut down on spill losses and diffusion associated with solvent filling. If the solvent is pumped into the cleaner with little or no splashing, such as with submerged fill piping, less solvent would be lost. Losses during transfer of contaminated solvent or sump bottoms from the OTVC sump to stills or waste solvent storage can be controlled by using leakproof couples. Transfer to a vented tank or sealed containers will help reduce emissions.

Solvent which has been contaminated with water should either be purified in a water separator or replaced with fresh solvent. Water contained in the solvent enhances diffusion losses (except for CFC-113 solvent).

Safety Switches. Control switches are devices used on vapor cleaners to prevent unsafe conditions such as vapor overflow, solvent decomposition, and excess solvent consumption. Common types of control switches include: (1) vapor level control thermostat; (2) condenser water pressure switch or flow switch and thermostat (for water cooled machines); (3) sump thermostat; (4) liquid solvent level control; (5) spray pump control switch and (6) secondary heater switch. The first four switches turn off the sump heat while the fifth turns off the spray when conditions within the machine exceed proper operating conditions. The most important switch is the vapor level control thermostat which turns off sump heat when the solvent vapor zone rises above the design operating level. The secondary heater switch, found on some machines, is activated when introduction of a large load causes the vapor level to fall. Secondary heaters reduce solvent loss from vapor level fluctuation.

As oils, greases, and other contaminants build up in the solvent, the boiling point of the mixture increases. Both the sump thermostat and liquid solvent level control prevent the solvent from becoming too hot and decomposing. The sump thermostat cuts off the heat when the sump temperature rises significantly above the solvent's boiling point, which will occur as contamination of solvent increases. The solvent level control turns off the heat when the liquid level of the boiling sump drops nearly to the height of the sump heater coils. In the case of electrically and corrosive decomposition products. For steam-heated units, or units which use a heat pump system, solvent decomposition is less likely because these heat sources normally do not reach solvent-decomposing temperatures.

However, solvent level controls can be useful on machines using these heat sources, especially for the higher boiling solvents, trichloroethylene and perchloroethylene, because low liquid levels permit high concentration of soils which can "bake" onto heating elements, seriously impairing heat transfer and possibly contributing to solvent decomposition. While these heat sources cannot reach temperatures where solvent decomposition is rapid, hotter mixtures of solvent and sludges can cause solvent deterioration more quickly than the cooler operating temperatures of relatively clean solvent. Therefore, a solvent level switch can still benefit by signalling the time for solvent cleanup.

The spray pump control switch is not used as often as the other safety switches, but it can offer a significant benefit. If the vapor level drops below a specified level, this control cuts off the spray pump until the normal vapor level is resumed, and then the spray can be manually re-started. This prevents spraying with an inadequate vapor level, which can cause excessive emissions of sprayed solvent. The spray pump control switch sometimes also has a feature which cuts off the spray pump if spraying is outside the vapor zone.

Although the effectiveness of these controls cannot be quantified, it is expected that these switches will protect against potentially significant emissions from upset conditions.

4.3 IN-LINE CLEANERS

In-line cleaners can be cold cleaners, vapor cleaners, or a combination cold/vapor cleaner. However, the majority using chlorinated/ chlorofluorinated solvents are vapor cleaners. These cleaners are nearly always enclosed except for entrance/exit ports and employ a continuous or multiple-batch loading systems. Unlike OTVC's which are often "off-the-shelf" items, they are normally custom-designed for a specific workload and production rate situation. In-line cleaners are used in a broad spectrum of metal working industries, but are most often found in plants where there is a constant stream of parts to be cleaned, and the advantages of continuous cleaning outweigh the lower capital cost of a batch loaded OTVC.

The control techniques applicable for use with a in-line cleaner vary according to the machine design and operation. Presented in this chapter are the following controls minimizing the entrance/exit openings, carbon adsorption, freeboard refrigeration devices, drying tunnels, rotating baskets, and hot vapor recycle/superheated vapor systems.

Test data were not available to evaluate the effectiveness of all the in-line cleaner control techniques listed above. Only four tests were available, three that evaluated the effectiveness of a freeboard refrigeration device (two below-freezing, one above-freezine) and the other a carbon adsorber. These tests are discussed in the relevant subsections and are summarized in Table 4-5.

TABLE 4-5. SUMMARY OF AVAILABLE TESTS - IN-LINE CLEANERS

			Baseline			Controlled			
Tested Control	Solvent	Cleaner Make	Seconday Chiller	Carbon Adsorber	Emission (lb/ft2/hr)	Secondary Chiller	Carbon Adsorber	Emission (lb/ft2/hr)	Control Efficiency
AFC	GENSOLV DFX	Allied	off	none	6.2 lb/hr	AFC	none	5.7 lb/hr	8
BFC	GENSOLV DFX	Allied	off	none	6.2 lb/hr	BFC	none	1.95 lb/hr	69
BFC	PCE	Detrex	off	none	1.0	BFC	none	0.4	62
CADS	TCE	Blakeslee	none	off	1.2	none	on	0.5	61

AFC = above-freezing freeboard refrigeration device
BFC = below-freezing freeboard refrigeration device
CADS = carbon adsorption system

4.3.1 Controls for Interface Emissions

4.3.1.1 Minimize Entrance/Exit Openings. Although in-line cleaners are mostly enclosed by design, additional emission control can be achieved by minimizing opening areas and covering the openings during non-operating hours. A reduction in the area of entrance and exit openings reduces idling and working losses due to diffusion by minimizing air drafts inside the cleaner. Air drafts increase emissions by sweeping away solvent-laden air near the air/solvent vapor interface and promoting mixing and diffusion by increasing turbulence in the freeboard area.

Among in-line cleaners, monorail cleaners tend to have the greatest diffusion emissions due to drafts through the machine caused by openings at opposite ends. In-line machines utilizing U-bend designs eliminate the problem of air currents flowing through the machine. Also, many in-line cleaners, such as monorail cleaners can be constructed so that internal baffles the effect of air flow through the machine (see Figure 4-14).

Silhouette openings and hanging flaps decrease the area where diffusion losses can occur and restrict drafts inside the cleaner, but will have minimal effect on emissions if the openings are already relatively small. When the in-line cleaner is not in use, port covers should be used to reduce downtime emissions.

The extent to which reduced entrance/exit opening area affects emissions is dependent on the total open area. The relative importance of use of port covers in overall emission reduction depends on the operating schedule. Port covers are most essential when the fraction of the daily schedule the cleaner spends in the downtime mode is substantial.

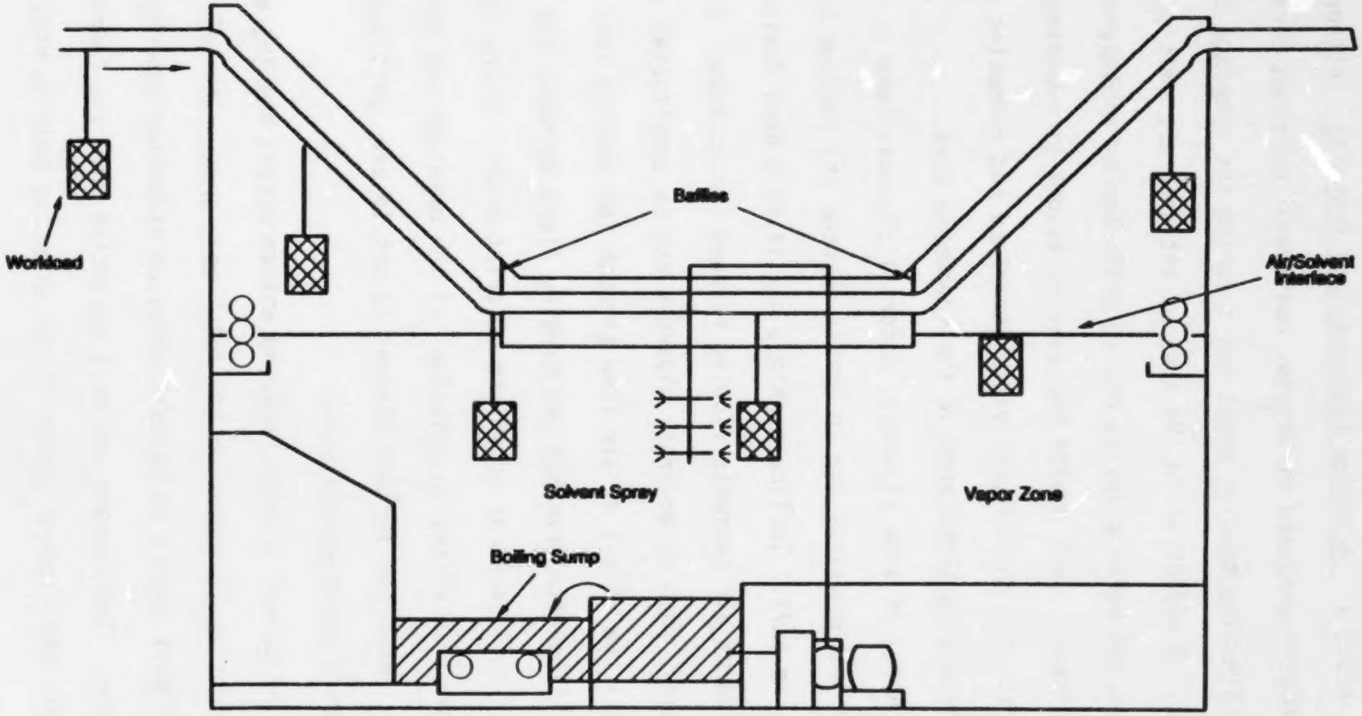
Baffles
Workload
Air/Solvent Interface
Solvent Spray
Vapor Zone
Boiling Sump
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Figure 4-14. Baffled Monorail In-line Cleaner

4.3.1.2 Carbon Adsorption. Venting solvent vapor emissions to a carbon adsorption system is a major emission control technology for both diffusion losses and workload related losses from in-line vapor cleaners and cold cleaners. Carbon adsorbers are effective emissions control devices and can be cost-effective since captured solvent is recycled. The enclosure around in-line cleaners makes it easier to capture and duct emissions to the carbon adsorber, and overall efficiencies are higher on in-lines than OTVC's. The relative degree of emissions control depends on the cleaner design, workload characteristics, and the solvent emissions capture efficiency. See Section 4.2.1.7 for more discussion of control by carbon adsorption.

The available test on carbon adsorbers shows approximately a 60 percent emissions reduction efficiency when applied to an in-line cleaner (i.e., circuit board stripper).[40] Carbon adsorbers are used in both conveyorized vapor and in-line cold cleaners in many applications. However, with some solvent mixtures, there could be the same operating problems described for OTVC's in Section 4.2.1.7.

4.3.1.3 Freeboard Refrigeration Devices. The refrigerated freeboard device on a in-line vapor cleaner functions in the same way as one on an OTVC. Refrigeration established a cool air layer above the vapor zone which inhibits diffusion and solvent-air mixing. (See Section 4.2.1.2 for a more detailed discussion of freeboard refrigeration devices.)

Only three tests evaluating the effect of freeboard refrigeration devices on in-line vapor cleaner emissions were available to EPA. One of these tests evaluated an above-freezing chiller and two evaluated below-freezing chillers on an in-line circuit board defluxer. The test data indicated that a below-freezing chiller can reduce in-line emissions by about 60 to 70 percent. Above-freezing chillers can achieve about a 10 percent emission reduction.[41,42]

4.3.2 Control for Workload Emissions

4.3.2.1 Drying Tunnels. A drying tunnel is simply an add-on enclosure which extends the exit area of in-line cleaners. The tunnel reduces carry-out losses because solvent evaporating from cleaned parts exiting the machine may be contained within the drying tunnel rather than being lost to the atmosphere. Much of the evaporated solvent in the drying tunnel will sink back into the vapor zone, thereby being recovered. Or, if the machine is connected to a carbon absorber, the evaporated solvent in the drying tunnel will be drawn into the absorber and recovered. A drying tunnel works well in conjunction with a carbon adsorber.

The effectiveness of a drying tunnel is dependent on several factors. Since drying tunnels primarily reduce carry-out emissions, the effectiveness of this device is dependent on the amount of carry-out before installation of the tunnel. The amount of control is also dependent on the length of time that the parts are in the drying tunnel. The length of time necessary will depend on the solvent type and the parts configuration. If sufficient time is allowed, essentially all carry-out emissions could be eliminated (except for the most intricate or "solvent trapping" types of parts).

A drawback to the use of a drying tunnel as a control device is the large amount of floor space that is required. The floor space may not be available in all plants to add drying tunnels to existing cleaners, although it can be planned for when new machines are purchased.

4.3.2.2 Rotating Baskets

Rotating baskets may be used to reduce carry-out emissions from cross-rod cleaners and ferris wheel cleaners or when cleaning parts that may trap solvent. A rotating basket is a perforated or wire mesh cylinder containing parts to be cleaned that is slowly rotated while proceeding through the cleaner. The rotation prevents trapping of liquid solvent on parts.

As with drying tunnels, the control effectiveness of rotating baskets is not easily quantifiable. The effectiveness is dependent on the workload shape and the way the parts are loaded into the basket.

Not all parts are able to be tumbled in baskets without being damaged. Therefore, rotating baskets are not applicable to all operations. Also, rotating baskets are designed into the conveyor and hence are not easily retrofitted on existing cleaners.

4.3.2.3 Hot Vapor Recycle/Superheated Vapor

Hot vapor recycle and superheated vapor are promising, relatively new technologies. Vendors are reporting that these technologies have the potential to significantly reduce carry-out emissions from both OTVC's and in-line vapor cleaners. An in-line cleaner equipped with superheated vapor is shown in Figure 4-15.

Both hot vapor recycle and superheated vapor operate on the same principle. These two technologies aim to create zones of superheated solvent vapor within the vapor layer. Cleaned parts are slowly passed through a superheated zone, warming the parts and evaporating liquid solvent on parts surfaces before they are withdrawn from the cleaner. Solvent vapor is heated to approximately 1.5 times the solvent boiling point.[43] (One contact indicated that solvent vapor is heated to the highest temperature possible without decomposing the solvent to speed drying.[44])

The hot vapor recycle process utilizes continuous recirculation of the solvent vapor. Solvent vapor is drawn from the vapor zone, circulated through a heater, and blown back into the vapor zone through a system of distribution slots. In the superheated vapor process, heating coils placed at one end of the vapor zone superheat a sector of solvent vapor through which cleaned parts are passed.

Hot vapor recycle is generally applicable only to in-line vapor cleaners since some type of enclosure is necessary for effective recirculation of solvent vapor. The movement of vapor creates turbulence and tends to increase solvent loss unless the machine is enclosed or baffles are present. Superheated vapor technology can reportedly be applied to both in-line cleaners or OTVC's. Hot vapor recycle and superheated vapor have been predominantly used with chlorofluorinated (CFC) solvents. The technologies are attractive due to potential savings of

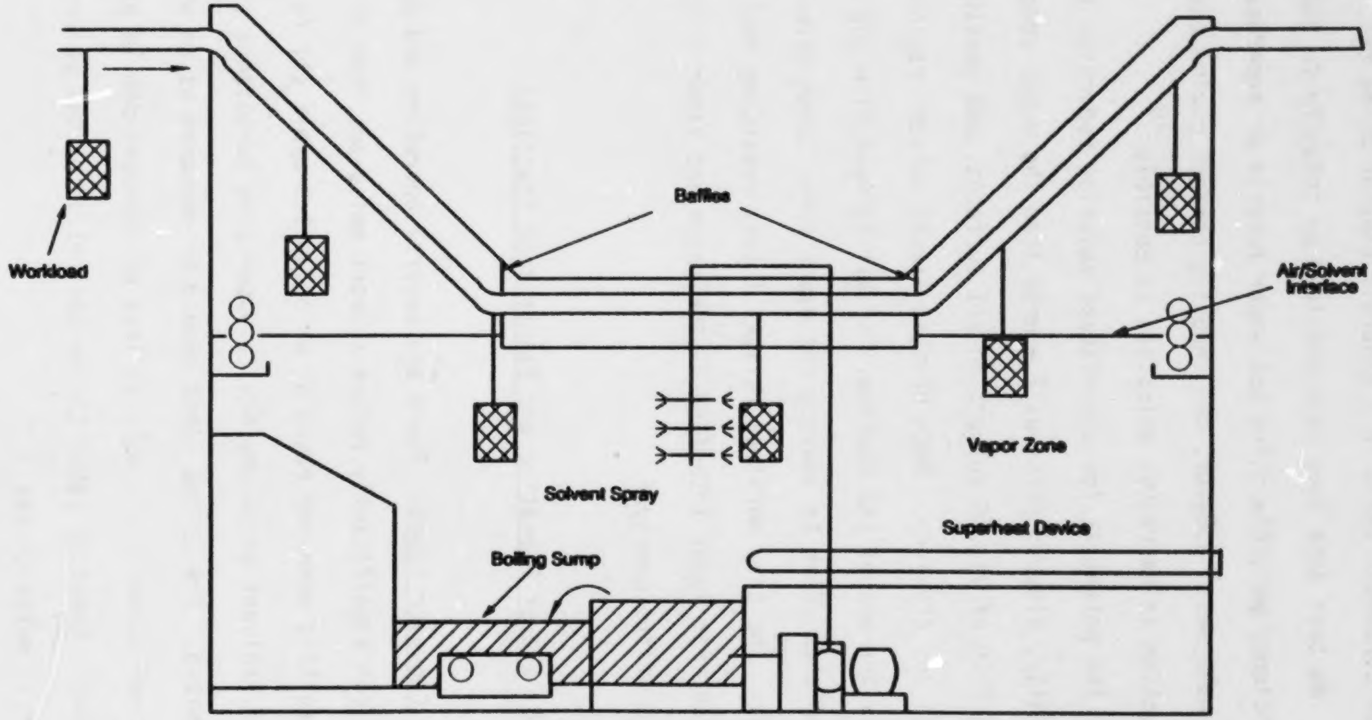
Baffles
Workload
Air/Solvent Interface
Vapor Zone
Solvent Spray
Superheat Device
Boiling Sump
1992772R

Figure 4-15. Baffled Monorail In-line Cleaner with Superheat Device

costly CFC solvents. Hot vapor recycle has been used in one application to clean condenser coils in a monorail cleaner using PCE.

No test data have been provided by industry to quantify the control efficiency possible using hot vapor recycle or superheated vapor technologies. However, one industry contact claims that a 90 percent reduction in carry-out emissions is possible.[45]

The potential for significant emission reduction is apparent. Normally, cleaned parts will emerge from the vapor zone of a cleaner with a thin film of liquid solvent on all surfaces, and possibly pooled solvent in holes and crevices. Much of this liquid solvent may not evaporate until parts are out of the machine. If all solvent film and pooled solvent is evaporated prior to leaving the vapor zone, large solvent savings should ensue. The only workload related losses remaining would be associated with air/solvent vapor interface disturbances and vapor entrainment due to the speed of the conveyor.

4.3.3 Proper Operating and Maintenance Practices

Conveyor Speed. There are several operating and maintenance practices that can significantly reduce solvent emissions from in-line cleaners. By controlling conveyor rates at or below 3.3 m/min (11 ft/min) absolute speed, solvent emissions due to vapor zone turbulence and carry-out can be minimized. The 11 fpm limit should be measured as an absolute rate, not a vertical speed (i.e., only 11 feet of conveyor should pass any spot in 1 minute). Conveyor rates can be controlled by the proper gearing of electric motor drives.

Spray Techniques. Emissions can be minimized by proper design of fixed spray systems. Nozzles should direct spray horizontally or downward to keep from piercing the vapor layer, or the spray area should be separated by baffles from the rest of the vapor zone.

Start-up/Shut-down Procedures. Losses can be reduced by the following methods: (1) starting the condenser water flow prior to turning on the sump to help condense excess loss as the vapor layer rises; (2) maintaining the condenser water flow after shut-down of the sump heater until the vapor layer has collapsed and the liquid solvent has cooled to room temperature; (3) cooling the sump during downtime or operating cooling coils above the sump; and (4) covering the entrance and exit ports during downtime.

Carbon Adsorber Procedures. For in-line cleaners with carbon adsorption systems, several operating practices can be employed which help to reduce emissions. The practices include (1) not by-passing the carbon adsorber during the desorption cycle, (2) proper carbon bed regeneration frequency, so as to prevent solvent breakthrough, (3) leak checks of the carbon adsorption system,and (4) good steam condensate separations.

Parts Drainage. As with OTVC's, an important operating practice that minimizes solvent carry-out in in-line operations is proper racking to avoid solvent puddles. Where pooling of solvent cannot be avoided, rotating or agitating parts prior to removal from the vapor layer to displace trapped solvent is necessary. Rotating baskets (discussed in Section 4.3.5) can also be used to limit liquid carry-out. The cleaning of porous or absorbent materials, which will absorb and carry out excessive quantities of solvent, must be avoided. Also, conveyor speed must be adjusted so that parts being cleaned are allowed to reach the solvent vapor temperature prior to removal from the vapor layer, and solvent is not visible on emerging parts.

Leak Detection/Repair. Solvent emissions can also be controlled by repairing visible leaks and repairing or replacing cracked gaskets, malfunctioning pumps, water separators, and steam traps promptly. Routine equipment inspections (particularly with a halide detector) will help locate leaks or problem areas more quickly. Leaks at welded joints can be avoided if the in-line cleaner vendor tests the joints prior to shipping. The test must be sensitive enough to detect fine cracks. A simple water test is not sufficient because high surface tension of water prevents penetration of small cracks. Often a dye penetrant is used. Machines made with 316L stainless steel walls will be less prone to stress cracks. Pressure fittings, as opposed to threaded connections, have also been reported to reduce leaks.

Clean out doors, viewing ports, or other gasketed machine parts must be carefully designed and manufactured. Gasket material must be nonporous and resistant to chemical attack of the solvents used. Ill-fitting gaskets or use of improper gasketing material can result in large solvent losses. One test of an in-line cleaner showed that inadequate sealing around a viewing door accounted for losses of 2.3 lbs/hour.[46] Sealing the window with duct tape eliminated these losses.

Solvent Transfer. Losses during transfer of solvent into and out of the in-line cleaner can be controlled by correct operating practices. Solvent filling and draining should be completed in as closed a system as possible. As stated previously, some vendors have systems that allow for pumping solvent from the solvent drum directly into the solvent cleaner. This could cut down on spill losses and diffusion associated with solvent filling. If the solvent is pumped into the cleaner with little or no splashing, such as with submerged piping, less solvent would be lost. Losses during transfer of contaminated solvent or sump bottoms from the in-line cleaner sump can be controlled by using leakproof couples. Transfer to a vented tank or sealed containers will help reduce emissions.

Safety Switches. In-line cleaners should also have the appropriate safety switches to ensure proper operation. A complete discussion of safety switches is included in Section 4.2.3.

4.4 COLD CLEANERS

As discussed in Chapter 3, carburetor cleaners are the only type of cold cleaner currently manufactured for use with a halogenated solvent. These machines are typically well controlled with a water cover. The water cover substantially limits evaporation losses since very little solvent comes into contact with the air. Many such machines are designed to be closed during the cleaning cycle (as well as during downtime and idling) and further reduce diffusion losses due to drafts and splashing of solvent. Based on one available test, water covers can reduce evaporation losses by at least 90 percent.[47] Existing cold cleaners using halogenated solvents should employ water covers to control evaporation.

Simple work practices can limit working losses. These practices include allowing adequate drainage of parts and flushing parts only within the confines of the cleaner.

4.5 INTEGRATED CONTROL STRATEGIES

This section defines the common elements of well-controlled solvent cleaning operations and gives specific examples of control technique combinations that constitute a well-controlled machine. Since solvent cleaner emissions stem from several sources, a well-controlled and operated machine will employ a variety of control measures. Purchasers of new equipment should seek equipment that is designed to provide these elements of good control. Owners and operators of existing cleaners can substantially reduce solvent loss by retrofitting the listed controls to an existing machine.

4.5.1 Summary of Solvent Loss Reduction Techniques

The two main elements of a well-controlled solvent cleaning operation are a good machine design and proper operating practices. A well-designed machine will have features to limit losses from: (1) diffusion and convection, (2) carryout, (3) leaks, (4) downtime, (5) solvent transfer, (6) water contamination, and (7) waste disposal. Proper operating practices involve minimizing or eliminating leaks, air drafts, spills, and solvent carryout.

Tables 4-6 through 4-8 summarize the available control techniques covered in this chapter. All of the good operating practices can be employed in any solvent cleaning operation. However, all listed control hardware would not be employed on one machine. There are several devices to control air/solvent vapor interface losses and workload related losses,

TABLE 4-6. AVAILABLE CONTROL TECHNIQUES FOR OTVC OPERATIONS

Source of Solvent Loss	Available Control Hardware	Operating Practices
Air/Solvent Vapor Interface	● 1.0 FBR (or higher) ● Freeboard refrigeration device ● Reduced primary condenser temperature ● Automated cover ● Enclosed design ● Carbon adsorber ● Reduced air/solvent vapor interface area	● Place machine where there are no drafts ● Close cover during idle periods
Workload	● Automated parts handling at 11 fpm or less ● Carbon adsorber ● Hot vapor recycle/superheated vapor system	● Rack parts so that solvent drains properly ● Conduct spraying at a downward angle and within the vapor zone ● Keep workload in vapor zone until condensation ceases ● Allow parts to dry within machine freeboard area before removal
Fugitive	● Sump cooling system for downtime ● Downtime cover ● Closed piping for solvent and waste solvent transfers ● Leakproof connections; proper materials of construction for machine parts and gaskets	● Routine leak inspection and maintenance ● Close cover during downtime

TABLE 4-7. AVAILABLE CONTROL TECHNIQUES FOR IN-LINE OPERATIONS

Solvent Loss Mechanism	Machine Design	Operating Practices
Air/Solvent Vapor Interface[b]	● 1.0 freeboard ratio ● Freeboard refrigeration device[a] ● Reduced primary condenser temperature[a] ● Carbon adsorber ● Minimized openings (clearance between parts and edge of machine opening is less than 10 cm or 10% of the width of the opening)	
Workload	● Conveyor speed at 11 fpm or less ● Carbon adsorber ● Hot vapor recycle/superheated vapor system	● Rack parts so that solvent drains properly ● Conduct spraying at a downward angle and within the vapor zone[a] ● Keep workload in vapor zone until condensation ceases ● Allow parts to dry within machine before removal
Fugitive	● Sump cooling system for downtime ● Downtime cover or flaps ● Closed piping for solvent and waste solvent transfers ● Leakproof connections; proper materials of construction for machine parts and gaskets	● Routine leak inspection and maintenance ● Cover ports during downtime

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[a] Applies to in-line vapor cleaners, but not in-line cold cleaners.

[b] Air/solvent interface for in-line cold cleaners.

TABLE 4-8. AVAILABLE CONTROL TECHNIQUES FOR COLD CLEANERS

Machine Design	Operating Practices
• Manual cover • Water cover with internal baffles • Drainage facility (internal)	• Close machine during idling and downtime • Drain cleaned parts for at least 15 seconds before removal • Conduct spraying only within the confines of the cleaner

and using them all would be redundant and expensive. The goal of minimum solvent loss can be met by selecting appropriate combinations of interface loss controls and workload loss controls. In Section 3.5.2, some workable combinations are described and evaluated.

4.5.2 Effective Control Technique Combinations

The effectiveness of various control technique combinations at reducing overall solvent cleaner emissions depends upon the operating schedule and the specific techniques combined. As noted in Section 3.5, the overall effectiveness of an individual control technique depends on the relative contribution of each emission type (idling, workload related, leaks, downtime, etc.) to total emissions. Those techniques that are effective at reducing the predominant emission type would be most effective at reducing overall solvent cleaner emissions. Furthermore, the combined control efficiency of two or more techniques that act on the same emission type (e.g., diffusion/convection losses) will be somewhat less than the sum of the efficiencies for each technique acting alone. Appendix A shows the derivation of a formula that can be used to calculate the overall efficiency of control technique combinations. Two or more control techniques acting on different emission types would have additive control efficiencies when acting in combination.

Table 4-9 presents estimates of the overall efficiencies associated with selected control technique options employed on uncontrolled machines described in Section 3.4. The control options include control technique combinations and, in the case of in-line cleaners, some single control technique options. The control technique options shown in

TABLE 4-9. EFFECTIVENESS OF SELECTED OTVC CONTROL TECHNIQUE COMBINATIONS

	Achievable Reduction (%)	
Control Technique Combination	Schedule A[a]	Schedule B[b]
• Hoist at 11 fpm Freeboard Refrigeration Device (BF) 1.0 FBR	40 - 50	50 - 70
• Hoist at 11 fpm Enclosed Design Sump Cooling	70 - 80	70 - 80
• Hoist at 11 fpm Automated Cover	30 - 40	50 - 60
• Hoist at 3 fpm Freeboard Refrigeration Device (BF) 1.0 FBR	50 - 60	80
• Hoist at 3 fpm Enclosed Design Sump Cooling	80 - 90	90
• Hoist at 3 fpm Automated Cover	40 - 50	80

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[a] Schedule A assumes the following: 6 hr/day idling; 2 hr/day working; and 16 hr/day downtime for 250 days/yr and 24 hr/day downtime for 105 day/hr. See Section 3.5 and Appendix B for relative proportion of total emissions due to idling, working, and downtime under this schedule.

[b] Schedule B assumes the following: 4 hr/day idling; 12 hr/day working; and 8 hr/day downtime for 250 days/yrs and 24 hr/day downtime for 105 days/yr.
See Section 3.5 and Appendix B for the relative proportion of total emissions due to idling, working, and downtime under this schedule.

this table are not meant to be an exhaustive list of the best interactive controls; other combinations are possible. For example, another in-line cleaner control option would involve combined hot vapor recycle or superheated vapor technology with a reduced primary condenser temperature. However, it is not the scope of this document to evaluate all possible control options.

Detailed calculations supporting the overall efficiencies of control technique combinations are contained in Appendices A and B. It should be noted that the estimated efficiencies assume that operating and maintenance practices are satisfactory. Improper practices may constitute a major source of cleaner emissions and may override the reductions achievable with the listed control techniques. If, for example, a machine has substantial losses due to leaks or filling, then the emission reductions shown in Tables 4-9 and 4-10 may not be realized.

4.6 ALTERNATIVE CLEANING AGENTS

Emissions of the five common halogenated solvents used in cleaning operations can be eliminated through conversion to alternative cleaning agents. Such cleaning agents include water or aqueous-based detergent, nonhalogenated solvent (e.g., terpene-based solutions) emulsion formulations, and new cleaning agents being introduced by solvent producers that are partially hydrogenated CFC's or blends of partially hydrogenated CFC's and other nonhalogenated solvents. Many vendors of cleaning equipment have indicated that there is a significant trend toward alternative cleaning systems due to concerns about potential health effects

TABLE 4-10. EFFECTIVENESS OF SELECTED IN-LINE CLEANER CONTROL TECHNIQUE COMBINATIONS

Control Technique Combination	Achievable Reduction (%) Schedule A[a]	Achievable Reduction (%) Schedule B[b]
• Freeboard Refrigeration Device	50	60
• Carbon Adsorption	50	60
• Carbon Adsorption, Sump Cooling	65	60
• Freeboard Refrigeration Device Sump Cooling	65	60
• Hot Vapor Recycle or Superheated Vapor, Sump Cooling	70	70
• Freeboard Refrigeration, Hot Vapor Recycle or Superheated Vapor	70	85

[a] Schedule A assumes the following: 8 hr/day working; 16 hr/day downtime for 260 days/yr and 24 hr/day downtime for 105 days/yr.

[b] Schedule B assumes the following: 16 hr/day working; 8 hr/day downtime for 365 days/yr.

and anticipated regulatory constraints associated with the halogenated solvents.

Effective alternative cleaning systems are currently being implemented to replace selected existing halogenated solvent applications. Several notable alternative systems are listed below:

- At the General Dynamics aircraft facility in Texas, staff researchers have tested aqueous and emulsion cleaners as substitutes for several TCE vapor degreasers. Several effective cleaning agents have been identified and plans are underway to replace the TCE degreasers.[48]
- At the US Air Force Aerospace and Meteorology Center in Ohio, a biodegradable detergent is now used in lieu of a CFC system to clean navigational equipment. At another Air Force base (Vandenburg), metals parts are now cleaned with an aqueous system instead of with TCA.[49,50]
- Rockwell International has evaluated the effectiveness of aqueous versus solvent ultrasonic cleaning at the Rocky Flats nuclear weapons facility in Colorado. The aqueous system was found to be more effective than both TCE and TCA systems.[51]
- The Torrington Company in Walhalla, South Carolina now uses an aqueous system to clean metal bearings for the automobile industry. Previously, vapor cleaners with TCA were used.[52]
- At AT&T in Massachusetts, a terpene based formulation is being used to clean printed circuit boards whereas methylene chloride had been used in the past.[53] Furthermore, General Electric in Waynesboro, Virginia has converted to an aqueous system to clean printed circuit boards.[54]

Despite the potential for increased substitution, there can be several disadvantages to alternative systems relative to solvent systems. These include: (1) increased space requirements since alternative systems are generally larger than comparable solvent systems: (2) potentially higher energy usages where alternative systems (particularly aqueous) require substantial energy to heat the cleaning fluid; (3) longer drying times or need for a separate dryer to remove water from parts being cleaned; and (4) increased wastewater discharge from disposal of contaminated cleaning fluid.[51-60] Also, if a substitution is made using cleaning agents containing VOC, the VOC emissions likely will have to be controlled.

There is some indication, however, that these disadvantages can be overcome. One manufacturer has developed an aqueous cleaner that features a drastically reduced wastewater problem and high cleaning efficiency. This type of cleaner relies on thorough agitation of a special cleaning fluid to keep oils in suspension (and not at the fluid surface) during the cleaning cycle which avoids recontamination of parts as they are extracted from the cleaner. Part of the cleaning fluid is continuously pumped to a separate non-agitated chamber where the oils will separate from the cleaning fluid and be drawn off by a surface skimmer. The "freshened" cleaning fluid can then be recycled to the cleaning tank.[61]

Still, there are some cleaning problems for which aqueous or terpene-based systems may not be suitable, usually because the necessary degree of cleaning cannot be achieved. Several examples noted by manufacturers of aqueous and solvent systems include silicon products in the electronics and medical industries; electronics industry applications where the circuitry is extremely close to the board (as in newer surface mount devices); wax-coated products, and adhesive products.[62,63] However, even more difficult cleaning situations may be handled by newly designed machines. Alternate cleaning technologies continue to improve.

In summary, alternative cleaning systems can replace existing solvent vapor cleaning systems in many applications. Compared to solvent systems, these alternative systems can be economically competitive and can achieve the same level of cleaning required. The feasibility of substitution, however, should be evaluated on a case-by-case basis.

The EPA will continue to make available information concerning alternative cleaning agents as ongoing investigations are completed. The Global Change Division of the Office of Atmospheric and Indoor Air Programs has been investigating alternative cleaning systems as part of stratospheric ozone depletion and global warming mitigation efforts. Several reports addressing alternative cleaning systems will be available in the near future.

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5.0 COST ANALYSIS

5.1 INTRODUCTION

This chapter presents costs and cost effectiveness values of various control options for emissions of methylene chloride (MC), perchloroethylene (PCE), trichloroethylene (TCE), 1,1,1 trichloroethane (TCA), and trichlorotrifluoroethane (CFC-113) from organic solvent cleaners. Cost analyses are provided for controlling emissions from open top vapor cleaners (OTVC's) and in-line (i.e., conveyorized) cleaners. From available information and as mentioned in Chapter 4, the only cold cleaner currently manufactured for use with a halogenated solvent is the carburetor cleaner, which is generally well-controlled at baseline with a water cover. As a result, no cost analyses were performed on cold cleaners.

Since organic solvent cleaners comprise a wide range of equipment types, sizes, and operating techniques, three model cleaner sizes were chosen, and two operating schedules were composed to evaluate the potential impacts of controlling solvent emissions. The individual technologies for controlling halogenated solvent emissions from organic solvent cleaners are presented in Chapter 4.

Due to the wide variation in solvent cleaner operating schedules, the most effective control options for a given cleaner may vary. In Chapter 4, example options for controlling emissions from OTVC's and in-line cleaners were presented. These options represent a collection of effective control techniques including controls for reducing losses from idling, working, and downtime. This chapter presents cost analyses for each control option presented in Chapter 4. Costs were calculated for new cleaners and for retrofit applications. However, only retrofit costs are presented in this chapter. Cost tables for new control equipment are included in Appendix C-3.

Section 5.2 presents a description of the overall cost methodology and assumptions. Sections 5.3 and 5.4 present the information for OTVC's and in-line cleaners, respectively. These sections present model cleaner parameters as well as cost effectiveness values. Available capital cost information on all control techniques presented in Chapter 4 are summarized in Appendix C-1. Annualized costs are detailed in Appendix C-2. Appendix C-3 includes all tables used in calculating cost effectiveness values for new and retrofit cases.

5.2 COSTING METHODOLOGY

This section presents a summary of the methodology used to estimate cost effectiveness of potential control options. The methodology outlined in this section can be used to determine the cost of other control options using the information contained in the appendices.

As described in Chapter 4, a complete control program consists of employing well-designed and manufactured equipment plus operating the equipment to minimize solvent loss. Aside from the hardware controls costed here, a number of solvent-saving practices in well controlled solvent cleaners cannot be readily accounted for in a cost effectiveness calculation. Examples of good operating practices include covering cleaning equipment whenever possible, properly using solvent sprays, preventing solvent spillage during solvent transfer, detecting and repairing leaks, proper racking of parts, and storing waste solvent in closed containers. Quantifying emission reductions due to these practices is difficult. However, some emission reduction is certain, unless all good operating practices are already rigorously followed . The costs are also difficult to quantify, but are expected to be minimal, primarily slightly more labor time to perform the tasks properly. As a result, it is anticipated that the cost effectiveness values presented in this chapter, for hardware controls only, are conservative estimates for situations where improved operating practices will accrue significant savings.

5.2.1 Model Cleaner Approach

Due to the large number of solvent cleaners and the wide variation in size of these cleaners, a model solvent cleaner approach was used. Models were developed to represent typical organic solvent cleaning operations and types of machines being sold today. The models are not intended to represent all machines, nor are they intended to represent any specific machine. Two operating schedules were selected for each model cleaner size to illustrate the effect operating schedule differences have on control device cost effectiveness.

The model solvent cleaner sizes used in this memorandum were based on the sizes reported in vendor responses to a questionnaire sent under

Section 114 of the Clean Air Act (CAA) to six of the largest vendors of solvent cleaners and follow-up with these and other vendors.[1-22] Sizes used by EPA in previous regulatory work under Section 111 of the CAA were also considered for inclusion. Based on air/solvent vapor interface area, the following solvent cleaner sizes were chosen:

OTVC's:	4.5ft^2, 16ft^2
In-line:	38ft^2

The in-line cleaner size, 38 ft^2, was used to represent both vapor and cold in-line cleaners. Cold in-line cleaners are photoresist stripping machines which use only MC. Specific model parameters will be presented in subsequent portions of this chapter.

5.2.2 Capital Costs

Capital costs include all the costs necessary to design, purchase, and install a particular control device or new equipment addition. A summary of capital costs used in this chapter is presented in Table 5-1. All available cost information for these and other control devices (described in Chapter 4) is included in Appendix C-1.

The basis for estimating control costs was primarily information contained in Section 114 questionnaire responses discussed above. Additional information was obtained through telephone contacts with several other vendors.[23-31] The Section 114 responses included information on model solvent cleaner sizes, control equipment costs, and operating requirements for control equipment. The costs for the model solvent cleaners were estimated from the

TABLE 5-1. CAPITAL COSTS (1988) USED IN COST ANALYSIS

	Total Installed Capital Costs ($)	
	New	Retrofit
Open Top Vapor Cleaners		
Small OTVC 4.5 ft^2		
Automated Parts Handling	1,500 - 2,000	1,500 - 2,000
Below-freezing FRD	4,500	5,400
Bi-Parting Cover	7,900	8,500
1.0 Freeboard Ratio	500	500
Enclosed Design	3,000	3,000
Sump Cooling	1,500	1,500
Large OTVC 16.0 ft^2		
Automated Parts Handling	3,000 - 3,500	3,000 - 3,500
Below-freezing FRD	8,600	10,300
Bi-Parting Cover	10,200	11,300
1.0 Freeboard Ratio	600	600
Enclosed Design	10,000	10,000
Sump Cooling	1,500	1,500
In-Line Cleaners 38.0 ft^2		
Below-freezing FRD	14,700	17,700
Carbon Adsorber	61,000	74,900
Super Heated Vapor	3,000	3,000

FRD - Freeboard refrigeration device

range of costs for cleaners of similar size to the model solvent cleaner sizes. Costs were also developed for two additional OTVC sizes (8.6 ft^2 and 38 ft^2). These costs are included in Appendix C-1.

Total installed capital costs reported in the vendor responses were for retrofit and new control equipment. Since these costs were reported as installed, they include sales taxes, freight, and installation charges. Average costs based on all vendor quotes for each model solvent cleaner and each control option were calculated. These average values were then adjusted using engineering judgement and the following considerations:

- The costs received from different vendors often varied for identical controls. In order for model solvent cleaner costs to best represent the industry, costs from larger vendors were weighted more heavily than the smaller vendor costs.

- Most manufacturers submitted costs for some, but not all, model solvent cleaner sizes. Also, as indicated above, the reported costs often varied significantly for identical controls. Consequently, there was the possibility that taking straight averages of cost of certain controls would not make sense. For example, using this approach, the costs associated with controls for larger size cleaners were sometimes less than for smaller cleaners, and retrofit costs were sometimes less than new costs. Costs were adjusted to eliminate these discrepancies.

- Some manufacturers responding to the questionnaire do not manufacture all the controls for which they provided costs. Their costs, therefore, included purchasing the control from another vendor plus a markup. Costs from these manufacturers were used only when they actually retrofitted a significant number of the control devices (as reported in the vendor questionnaires and in follow-up contacts). Estimates of operating costs were also adjusted to reflect the values obtained from vendors actually supplying the controls.

A detailed discussion of the derivation of specific capital costs for each model cleaner is included in Appendix C-1. A description of the items costed for each control technique is listed below:

- automated parts handling: The costs for an automated parts handling system includes a range. The lower cost in each size range is for a push-button hoist capable of moving at a constant 11 fpm. The higher cost is for a push-button hoist capable of moving at 11 fpm, except when moving through the air/solvent vapor interface and freeboard area, when it moves at 3 fpm. The system for the small OTVC has a 30 lb capacity and for the large OTVC has a 100 to 200 lb. capacity.

- below-freezing freeboard refrigeration device: The costs for this control technique are based on the costs for units approximately the size of each of the model units listed above. The costs include the coiled tubing that are lowered into the solvent cleaner as well as the required compressor for the refrigerant. [The above-freezing freeboard refrigeration devices included in Appendix C-1 are assumed to be water cooled.]

- bi-parting cover: The costs for a bi-parting cover are based on a wide range of vendor quotes as described in Appendix C-1. The costs presented include estimated costs for the bi-parting mylar cover as well as the motors to run the covers.

- 1.0 freeboard ratio: The costs for an increased freeboard ratio include only the cost of a stainless steel extension to the freeboard. Any engineering costs would be incurred only once for each model and were, therefore, not included in costs for individual owners and operators.

- enclosed design: The costs for an enclosed design includes the cost to add an enclosure to the top of an open-top vapor cleaner. The enclosure, depicted in Figure 4-b, has a vertical opening. The costs do not include the costs of an automated parts handling system that would be necessary with an enclosed design.

- sump cooling: The costs for sump cooling include the cost of a coil located directly above the solvent sump, as well as the necessary compressor.

- carbon adsorber: The costs for a carbon adsorption system include two activated carbon beds, a blower, and a condenser.

- super-heated vapor: The costs for a super-heated vapor include the cost for heating coils and extenstion to the cleaner at the exit area.

Since all costs are based on a range of vendor quotes, actual costs experienced by individual machine operators will vary. However, the costs presented are considered to be representative of average costs nationwide.

Capital costs were annualized based on an annual percentage rate of 10 percent and the following equipment lifetimes based on vendor questionnaires:

OTVC:	10 years[32,33,34]
In-line:	15 years[35,36,37]

All controls except carbon adsorbers were assumed to have the same lifetime as the solvent cleaner. A carbon adsorber has a reported lifetime of 10 years and was annualized over this life span.[38]

5.2.3 Annual Operating Costs

Annual operating costs associated with solvent cleaner emission controls include such items as annualized capital charges, added labor, electricity, cooling water and steam, floor space, and other miscellaneous costs incurred due to use of each control. A summary of the operating cost parameters are included in Table 5-2. Operating cost derivations are detailed in Appendix C-2. Steam costs are calculated for the steam necessary to desorb carbon adsorber beds. Additional cooling water is also required for carbon adsorption systems to condense the solvent-laden steam after desorption. The additional floor space required for each control device is also costed where appropriate. Additional floor space requirements were based on manufacturers specifications.

In addition to calculating the increased annual operating costs, a credit is calculated for the reduction in solvent emissions credited to the control device. A reduction in emissions translates into a corresponding reduction in solvent consumption, thus saving the operator solvent expense. The credit is calculated using the solvent costs presented in Table 5-2.

5.3 OPEN TOP VAPOR CLEANERS

5.3.1 Model Cleaner Parameters

Open top vapor cleaners typically range in size from approximately 4 ft^2 to greater than 50 ft^2, though the majority of cleaners are less than 20 ft^2. The model cleaners used in this chapter to analyze control costs were selected to be representative of this range. The two model sizes are 4.5 ft^2 and 16 ft^2. The model cleaner parameters for OTVC's are presented in Table 5-3. The parameters are based on industry contacts and EPA studies of the solvent cleaning industry.

TABLE 5-2. SUMMARY OF OPERATING COST PARAMETERS

	Original Quoted Cost	Year	1988 Cost	Reference
Material				
Methylene Chloride			\$0.259/lb	39
Perchloroethylene			\$0.31/lb	40
Trichloroethylene			\$0.385/lb	41
1,1,1 Trichloroethane			\$0.405/lb	42
Trichlorotrifluoroethane			\$0.90/lb	43
Utility				
Electricity	\$.0713/kWh	1986	\$.0780/kWh	44
Steam	\$5.65/1000 lb	1984	\$5.98/1000 lb	45
Cooling Water	\$0.08/1000 gal	1980	\$0.099/1000 gal	46
Labor				
Operating Labor	\$7.87/manhour	1977	\$13.78/manhour	47
Maintenance Labor	\$8.66/manhour	1977	\$15.16/manhour	47
Miscellaneous				
Additional Space	42/ft^2	1980	55.7/ft^2	48

Utilities and labor rates (operating and maintenance) were increased using Bureau of[49] Labor Statistics (BLS) producer price indices. These are as follows:

4th quarter 1977 - 62.5
1980 - 88.0
1984 - 103.3
1986 - 100.0
1988 - 109.4

Building space costs were increased from 1980 to 1986 dollars using CE plant cost indices for building. These are as follows:

November 1980 (final) - 244.7[50]
November 1986 (final) - 304.4[51]
November 1986 (prelim) - 324.4[52]

As shown in Table 5-3, two operating schedules were evaluated for each model cleaner size. These schedules were selected to represent the wide range of operating schedules that exist in solvent cleaning operations and were detailed in Chapter 3.

Based on correspondence with industry concerning characteristics of cleaners manufactured over the last several years, an OTVC has a freeboard ratio of 0.75, a manual cover used in downtime, a primary condenser temperature of approximately 75°F, and the appropriate safety switches.[40,41,42] As discussed in Section 3.4, uncontrolled emissions were calculated for losses due to idling, working, and downtime emission rates. Uncontrolled emissions from OTVC's were estimated to be 2,890 lb/year and 6,940 lb/year for the small OTVC under schedules A and B, respectively. Uncontrolled emissions from the large OTVC were estimated at 10,300 lb/year and 24,700 lb/year for operating schedules A and B, respectively.

No emission reduction credit or control cost has been included for use of the cover during downtime and idle time or for the operation of safety switches since these are assumed to be common practice at baseline. The following six control options were considered as control alternatives:

- Control Option 1: an automated parts handling system operating at 11 fpm, a below-freezing freeboard refrigeration device, and a 1.0 freeboard ratio;
- Control Option 2: an automated parts handling system operating at 11 fpm, an enclosed design, and sump cooling during downtime;

- Control Option 3: an automated parts handling system operating at 11 fpm, and a bi-parting cover capable of being closed during operation;

- Control Option 4: an automated parts handling system operating at 3 fpm (when parts are entering/leaving the vapor zone), a below-freezing freeboard refrigeration device, and a 1.0 FBR;

- Control Option 5: an automated parts handling system operating at 3 fpm (when parts are entering/leaving the vapor zone), an enclosed design, and sump cooling; and

- Control Option 6: an automated parts handling system operating at 3 fpm (when parts are entering/leaving the vapor zone), and a bi-parting cover capable of being closed during operations;

Based on the existing test data, ranges of efficiencies for each individual control device were estimated. The overall control efficiency was calculated by summing individual control efficiencies for each device in an option, weighted according to the amount of time per year that the emissions of each type (idling, working, downtime) occurred. The overall efficiency differs for different operating schedules. A more complete discussion of control efficiency derivations is included in Appendix B.

The ranges of efficiencies for each control option for each operating schedule are summarized at the bottom of Table 5-3. It should be noted that all reported efficiencies include only the control of the three primary emission types. They do not account for leaks, wastewater losses, or transfer losses which should be minimal if proper practices are employed. However, if another emission type is not controlled (such as an undetected leak) and becomes a major source, then the efficiencies reported in Table 5-3 are overstated. In general, Control Option 5 had the highest overall control efficiency, ranging up to 90 percent control. Control Option 2 was generally the next most effective, except for the large OTVC under Schedule B where Control Option 6 has the second highest efficiency. Control Options 1 and 3 generally have the lowest overall efficiencies.

5.3.2 Model OTVC Cost Evaluation

Table 5-4 shows the capital costs, annualized operating costs, emission reduction, solvent recovery credit, net annualized control costs, and cost effectiveness of each of these options for a model OTVC using MC. Tables 5-5 through 5-8 summarize this information for PCE, TCE, TCA, and CFC-113, respectively. The tables detailing these costs (and presenting the values for new OTVC's) are presented in Appendix C-3.

Generally, the ranking of the cost effectiveness values was independent of solvent type. The only variable among the calculations for each solvent was the solvent price (listed in Table 5-2). Therefore, the higher priced solvents generate higher solvent recovery credits and, therefore, lower net

TABLE 5-3. MODEL CLEANER PARAMETERS FOR OPEN TOP VAPOR CLEANERS

Parameter				Small - Schedule A		
Working area, ft^2				4.5		
Solvent				All		
Operating schedule hr/year						
Idling				1560		
Working				520		
Downtime				6656		
Uncontrolled emission rates lb/hr						
Idling				0.675		
Working				1.800		
Downtime				0.135		
Uncontrolled emissions[a] (lb/yr)						
Idling				1050		
Working				940		
Downtime				900		
Total				2890		
Control Option	1	2	3	4	5	6
Controlled emissions[b] (lb/yr) Total[c]	1730-1440	870-580	2020-1730	1440-1160	580-290	1730-1440
Emission Reduction	1160-1440	2020-2310	870-1160	1440-1730	2310-2600	1160-1440

[a] Uncontrolled emissions based on 0.75 FBR, cover in downtime.

[b] Controlled emissions based on the following:

	Efficiency Range (%)
Control Option 1: Automated Parts Handling System @ 11 fpm; Below-freezing FRD; 1.0 FBR	40 - 50
Control Option 2: Automated Parts Handling System @ 11 fpm; Enclosed Design; Sump Cooling	70 - 80
Control Option 3: Automated Parts Handling System @ 11 fpm; Automated Bi-parting Cover	30 - 40
Control Option 4: Automated Parts Handling System @ 3 fpm; Below-freezing FRD; 1.0 FBR	50 - 60
Control Option 5: Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	80 - 90
Control Option 6: Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	40 - 50

[c] Range based on range of Control Efficiencies

FRD - Freeboard refrigeration devices

FBR - Freeboard ratio

NOTE: All reported efficiencies are for control of idling, working, and downtime losses only. They do not account for leaks, wastewater losses, or transfer losses which should be minimal if proper practices are employed.

TABLE 5-3. MODEL CLEANER PARAMETERS FOR OPEN TOP VAPOR CLEANERS (Continued)

Parameter				Small - Schedule B		
Working area, ft^2				4.5		
Solvent				All		
Operating schedule hr/year						
Idling				1560		
Working				520		
Downtime				6656		
Uncontrolled emission rates lb/hr						
Idling				0.675		
Working				1.800		
Downtime				0.135		
Uncontrolled emissions[a] (lb/yr)						
Idling				700		
Working				5620		
Downtime				620		
Total				6940		
Control Option	1	2	3	4	5	6
Controlled emissions[b] (lb/yr) Total[c]	3470-2080	2080-1390	3470-2770	1390	690	1390
Emission Reduction	3470-4860	4860-5550	3470-4160	5550	5240	5550

[a] Uncontrolled emissions based on 0.75 FBR, cover in downtime.

[b] Controlled emissions based on the following:

	Efficiency Range (%)
Control Option 1: Automated Parts Handling System @ 11 fpm; Below-freezing FRD; 1.0 FBR	50 - 70
Control Option 2: Automated Parts Handling System @ 11 fpm; Enclosed Design; Sump Cooling	70 - 80
Control Option 3: Automated Parts Handling System @ 11 fpm; Automated Bi-parting Cover	50 - 60
Control Option 4: Automated Parts Handling System @ 3 fpm; Below-freezing FRD; 1.0 FBR	80
Control Option 5: Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	90
Control Option 6: Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	80

[c] Range based on range of Control Efficiencies

FRD - Freeboard refrigeration devices

FBR - Freeboard ratio

NOTE: All reported efficiencies are for control of idling, working, and downtime losses only. They do not account for leaks, wastewater losses, or transfer losses which should be minimal if proper practices are employed.

TABLE 5-3. MODEL CLEANER PARAMETERS FOR OPEN TOP VAPOR CLEANERS (Continued)

Parameter				Large - Schedule A		
Working area, ft^2				16.0		
Solvent				All		
Operating schedule hr/year						
Idling				1560		
Working				520		
Downtime				6656		
Uncontrolled emission rates lb/hr						
Idling				2.40		
Working				6.40		
Downtime				0.48		
Uncontrolled emissions[a] (lb/yr)						
Idling				3740		
Working				3330		
Downtime				3200		
Total				10270		
Control Option	1	2	3	4	5	6
Controlled emissions[b] (lb/yr) Total[c]	6160-5130	3080-2050	7190-6160	5730-4110	2050-1030	6160-5130
Emission Reduction	4110-5130	7190-8210	3080-4110	5130-6160	8210-9240	4110-5130

[a] Uncontrolled emissions based on 0.75 FBR, cover in downtime.

[b] Controlled emissions based on the following:

		Efficiency Range (%)
Control Option 1:	Automated Parts Handling System @ 11 fpm; Below-freezing FRD; 1.0 FBR	40 - 50
Control Option 2:	Automated Parts Handling System @ 11 fpm; Enclosed Design; Sump Cooling	70 - 80
Control Option 3:	Automated Parts Handling System @ 11 fpm; Automated Bi-parting Cover	30 - 40
Control Option 4:	Automated Parts Handling System @ 3 fpm; Below-freezing FRD; 1.0 FBR	50 - 60
Control Option 5:	Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	80 - 90
Control Option 6:	Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	40 - 50

[c] Range based on range of Control Efficiencies

FRD - Freeboard refrigeration devices

FBR - Freeboard ratio

NOTE: All reported efficiencies are for control of idling, working, and downtime losses only. They do not account for leaks, wastewater losses, or transfer losses which should be minimal if proper practices are employed.

TABLE 5-3. MODEL CLEANER PARAMETERS FOR OPEN TOP VAPOR CLEANERS (Continued)

Parameter	Large - Schedule B					
Working area, ft^2	16.0					
Solvent	All					
Operating schedule hr/year						
Idling	1560					
Working	520					
Downtime	6656					
Uncontrolled emission rates lb/hr						
Idling	2.40					
Working	6.40					
Downtime	0.48					
Uncontrolled emissions[a] (lb/yr)						
Idling	2500					
Working	19970					
Downtime	2200					
Total	24670					
Control Strategy	1	2	3	4	5	6
Controlled emissions[b] (lb/yr) Total[c]	12300-7400	7400-4930	12300-9860	4930	2470	4930
Emission Reduction	12300-17300	17300-19700	12300-14800	19700	22200	19700

[a] Uncontrolled emissions based on 0.75 FBR, cover in downtime.

[b] Controlled emissions based on the following:

	Efficiency Range (%)
Control Strategy 1: Automated Parts Handling System @ 11 fpm; Below-freezing FRD; 1.0 FBR	50 - 70
Control Strategy 2: Automated Parts Handling System @ 11 fpm; Enclosed Design; Sump Cooling	70 - 80
Control Strategy 3: Automated Parts Handling System @ 11 fpm; Automated Bi-parting Cover	50 - 60
Control Strategy 4: Automated Parts Handling System @ 3 fpm; Below-freezing FRD; 1.0 FBR	80
Control Strategy 5: Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	90
Control Strategy 6: Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	80

[c] Range based on range of Control Efficiencies

FRD - Freeboard refrigeration devices

FBR - Freeboard ratio

NOTE: All reported efficiencies are for control of idling, working, and downtime losses only. They do not account for leaks, wastewater losses, or transfer losses which should be minimal if proper practices are employed.

Table 5-4. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL OTVC's USING METHYLENE CHLORIDE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Automated Parts Handling System @11 fpm; Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,180	2,200	1,160- 1,440	(1,040)-(1,300)	1,170-900	1.0 - 0.6
	4.5ft2/B	8,180	2,770	3,470- 4,860	(900)-(1,260)	1,880-1,520	0.5 - 0.3
	16 ft2/A	15,200	3,630	4,110- 5,130	(1,060)-(1,330)	2,570-2,300	0.6 - 0.4
	16 ft2/B	15,200	4,200	12,300-17,300	(3,190)-(4,470)	(1,010)-(270)	0.1 -(0.02)
2. Automated Parts Handling System @11 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,220	1,820	2,020- 2,310	(520)-(600)	1,300-1,220	0.6 - 0.5
	4.5ft2/B	6,220	1,790	4,860- 5,550	(1,260)-(1,440)	530-350	0.1 - 0.06
	16 ft2/A	14,700	3,740	7,190- 8,210	(1,860)-(2,130)	1,880-1,610	0.9 - 0.3
	16 ft2/B	1,470	3,640	17,300-19,700	(4,470)-(5,110)	(830)-(1460)	0.2 -(0.05)
3. Automated Parts Handling System @11 fpm; Automated Bi-parting Cover	4.5ft2/A	10,200	2,090	870- 1,160	(220)-(300)	1,870-1,790	2.2 - 1.6
	4.5ft2/B	10,220	2,200	3,470- 4,160	(900)-(1,080)	1,300-1,120	0.4 - 0.3
	16 ft2/A	14,500	2,980	3,080- 4,110	(800)-(1,060)	2,180-1,920	0.7 - 0.5
	16 ft2/B	14,500	3,160	12,300-14,800	(3,190)-(3,830)	(30)-(670)	0 -(0.1)
4. Automated Parts Handling System @ 3 fpm Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,680	2,300	1,440- 1,730	(370)-(450)	1,930-1,860	1.3 - 1.1
	4.5ft2/B	8,680	2,880	5,550	(1,440)	1440	0.3
	16 ft2/A	15,700	3,740	5,130- 6,160	(1,330)-(1,600)	2,410-2,140	0.5 - 0.4
	16 ft2/B	15,700	4,310	19,700	(5,110)	(800)	(0.04)
5. Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,720	1,920	2,310- 2,600	(600)-(670)	1,320-1,250	0.6 - 0.5
	4.5ft2/B	6,720	1,890	6,240	(1,620)	270	0.04
	16 ft2/A	15,200	3,840	8,210- 9,240	(2,130)-(2,390)	1,710-1,440	0.2 - 0.2
	16 ft2/B	15,200	3,750	22,200	(5,750)	2,000	0.1
6. Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	4.5ft2/A	10,700	2,200	1,160- 1,440	(300)-(370)	1,900-1,820	1.6 - 1.3
	4.5ft2/B	10,700	2,300	5,550	(1,440)	860	0.2
	16 ft2/A	15,000	3,080	4,110- 5,130	(1,060)-(1,330)	2,020-1,750	0.5 - 0.3
	16 ft2/B	15,000	3,260	19,700	(5,110)	1,850	0.1

FRD = freeboard refrigeration device
OPERATING SCHEDULES:
Schedule A: 6 hours idling; 2 hours working; 16 hours downtime; 5 days/week; 52 weeks/year
Schedule B: 4 hours idling; 12 hours working; 8 hours downtime; 5 days/week; 52 weeks/year

Table 5-5. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL OTVC's USING PERCHLOROETHYLENE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Automated Parts Handling System @11 fpm; Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,180	2,200	1,160- 1,440	(360)-(450)	1,850- 1,760	1.6 - 1.2
	4.5ft2/B	8,180	2,770	3,470- 4,860	(1,080)-(1,500)	1,700- 1,270	0.5 - 0.3
	16 ft2/A	15,200	3,630	4,110- 5,130	(1,270)-(1,590)	2,360- 2,040	0.6 - 0.4
	16 ft2/B	15,200	4,200	12,300-17,300	(3,820)-(5,350)	380-(1,150)	0.03 -(0.1)
2. Automated Parts Handling System @11 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,220	1,820	2,020- 2,310	(630)-(720)	1,190- 1,100	0.6 - 0.5
	4.5ft2/B	6,220	1,790	4,860- 5,550	(1,500)-(1,720)	280- 70	0.06 - 0.01
	16 ft2/A	14,700	3,740	7,190- 8,210	(2,230)-(2,550)	1,510- 1,190	0.2 - 0.1
	16 ft2/B	1,470	3,640	17,300-19,700	(5,350)-(6,120)	(1,710)-(2,470)	(0.05)-(0.07)
3. Automated Parts Handling System @11 fpm; Automated Bi-parting Cover	4.5ft2/A	10,200	2,090	870- 1,160	(270)-(360)	1,820- 1,740	2.2 - 1.6
	4.5ft2/B	10,220	2,200	3,470- 4,160	(1,080)-(1,290)	1,120- 910	0.3 - 0.2
	16 ft2/A	14,500	2,980	3,080- 4,110	(960)-(1,270)	2,020- 1,710	0.7 - 0.4
	16 ft2/B	14,500	3,160	12,300-14,800	(3,820)-(4,590)	(660)-(1,420)	(0.05)-(0.1)
4. Automated Parts Handling System @ 3 fpm Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,680	2,300	1,440- 1,730	(450)-(540)	1,860- 1,770	1.3 - 1.1
	4.5ft2/B	8,680	2,880	5,550	(1720)	1,160	0.2
	16 ft2/A	15,700	3,740	5,130- 6,160	(1,590)-(1,910)	2,140- 1,830	0.4 - 0.3
	16 ft2/B	15,700	4,310	19,700	(6,120)	(1,810)	(0.04)
5. Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,720	1,920	2,310- 2,600	(720)-(810)	1,200- 1,120	0.6 - 0.5
	4.5ft2/B	6,720	1,890	6,240	(1,940)	50	0.01
	16 ft2/A	15,200	3,840	8,210- 9,240	(2,550)-(2,860)	1,290- 970	0.2 - 0.1
	16 ft2/B	15,200	3,750	22,200	(6,880)	(3,130)	(0.1)
6. Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	4.5ft2/A	10,700	2,200	1,160- 1,440	(360)-(450)	1,840-1,750	1.6 - 1.3
	4.5ft2/B	10,700	2,300	5,550	(1,720)	581	0.1
	16 ft2/A	15,000	3,080	4,110- 5,130	(1,270)-(1,590)	1,810-1,490	0.4 - 0.3
	16 ft2/B	15,000	3,260	19,700	(6,120)	(2,850)	(0.1)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 6 hours idling; 2 hours working; 16 hours downtime; 5 days/week; 52 weeks/year
Schedule B: 4 hours idling; 12 hours working; 8 hours downtime; 5 days/week; 52 weeks/year

Table 5-6. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL OTVC's USING TRICHLOROETHYLENE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Automated Parts Handling System @11 fpm; Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,180	2,200	1,160- 1,440	(440)-(560)	1,760- 1,650	1.5 - 1.1
	4.5ft2/B	8,180	2,770	3,470- 4,860	(1,340)-(1,870)	1,440- 900	0.4 - 0.2
	16 ft2/A	15,200	3,630	4,110- 5,130	(1,580)-(1,980)	2,050- 1,660	0.5 - 0.3
	16 ft2/B	15,200	4,200	12,300-17,300	(4,750)-(6,650)	(540)-(2,440)	(0.04)-(0.14)
2. Automated Parts Handling System @11 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,220	1,820	2,020- 2,310	(780)-(890)	1,040- 930	0.5 - 0.4
	4.5ft2/B	6,220	1,790	4,860- 5,550	(1,870)-(2,140)	(80)- (350)	(0.02)-(0.06)
	16 ft2/A	14,700	3,740	7,190- 8,210	(2,770)-(3,160)	970- 570	0.1 - 0.07
	16 ft2/B	1,470	3,640	17,300-19,700	(6,650)-(7,600)	(3,000)-(3,950)	(0.2)-(0.2)
3. Automated Parts Handling System @11 fpm; Automated Bi-parting Cover	4.5ft2/A	10,200	2,090	870- 1,160	(330)-(450)	1,760- 1,650	2.0 - 1.4
	4.5ft2/B	10,220	2,200	3,470- 4,160	(1,340)-(1,600)	860- 600	0.2 - 0.1
	16 ft2/A	14,500	2,980	3,080- 4,110	(1,190)-(1,580)	1,790- 1,400	0.6 - 0.3
	16 ft2/B	14,500	3,160	12,300-14,800	(4,750)-(5,700)	(1,580)-(2,540)	(0.1)-(0.2)
4. Automated Parts Handling System @ 3 fpm Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,680	2,300	1,440- 1,730	(560)-(670)	1,750- 1,640	1.2 - 1.0
	4.5ft2/B	8,680	2,880	5,550	(2,140)	740	0.1
	16 ft2/A	15,700	3,740	5,130- 6,160	(1,980)-(2,370)	1,760- 1,360	0.3 - 0.2
	16 ft2/B	15,700	4,310	19,700	(7,600)	(3,290)	(0.01)
5. Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,720	1,920	2,310- 2,600	(890)-(1,000)	1,030- 920	0.5 - 0.4
	4.5ft2/B	6,720	1,890	6,240	(2,400)	(510)	(0.1)
	16 ft2/A	15,200	3,840	8,210- 9,240	(3,160)-(3,560)	680- 280	0.1 - 0.03
	16 ft2/B	15,200	3,750	22,200	(8,550)	(4,800)	(0.2)
6. Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	4.5ft2/A	10,700	2,200	1,160- 1,440	(450)-(560)	1,750- 1,640	1.5 - 1.1
	4.5ft2/B	10,700	2,300	5,550	(2,140)	160	(0.03)
	16 ft2/A	15,000	3,080	4,110- 5,130	(1,580)-(1,980)	1,500- 1,105	0.4 - 0.2
	16 ft2/B	15,000	3,260	19,700	(7,600)	(4,330)	(0.2)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 6 hours idling; 2 hours working; 16 hours downtime; 5 days/week; 52 weeks/year

Schedule B: 4 hours idling; 12 hours working; 8 hours downtime; 5 days/week; 52 weeks/year

Table 5-7. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL OTVC's USING 1,1,1-TRICHLOROETHANE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Automated Parts Handling System @11 fpm; Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,180	2,200	1,160- 1,440	(470)-(580)	1,740-1,620	1.5 - 1.1
	4.5ft2/B	8,180	2,770	3,470- 4,860	(1,400)-(1,970)	1,370-810	0.4 - 0.2
	16 ft2/A	15,200	3,630	4,110- 5,130	(1,660)-(2,080)	1,970-1,560	0.5 - 0.3
	16 ft2/B	15,200	4,200	12,300-17,300	(4,990)-(6,990)	(790)-(2,790)	(0.1) -(0.2)
2. Automated Parts Handling System @11 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,220	1,820	2,020- 2,310	(820)-(940)	1,000-890	0.5 - 0.4
	4.5ft2/B	6,220	1,790	4,860- 5,550	(1,970)-(2,250)	(180)-(460)	(0.04)-(0.1)
	16 ft2/A	14,700	3,740	7,190- 8,210	(2,910)-(3,330)	820-410	0.1 - 0.05
	16 ft2/B	1,470	3,640	17,300-19,700	(6,990)-(7,990)	(3,350)-(4,340)	(0.2)-(0.2)
3. Automated Parts Handling System @11 fpm; Automated Bi-parting Cover	4.5ft2/A	10,200	2,090	870- 1,160	(350)-(470)	1,740-1,620	2.0 - 1.4
	4.5ft2/B	10,220	2,200	3,470- 4,160	(1,400)-(1,690)	820-510	0.2 - 0.1
	16 ft2/A	14,500	2,980	3,080- 4,110	(1,250)-(1,660)	1,730-1,320	0.6 - 0.3
	16 ft2/B	14,500	3,160	12,300-14,800	(4,990)-(5,990)	(1,830)-(2,830)	(0.1)-(0.2)
4. Automated Parts Handling System @ 3 fpm Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,680	2,300	1,440- 1,730	(580)-(700)	1,720-1,600	1.2 - 0.9
	4.5ft2/B	8,680	2,880	5,550	(2,250)	630-350	0.1
	16 ft2/B	15,700	3,740	5,130- 6,160	(2,080)-(2,500)	1,660-1,240	0.3 - 0.2
	16 ft2/B	15,700	4,310	19,700	(7,600)	(3,680)-(4,680)	(0.2)
5. Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,720	1,920	2,310- 2,600	(940)-(1,050)	900-870	0.4 - 0.3
	4.5ft2/B	6,720	1,890	6,240	(2,530)	(640)	(0.1)
	16 ft2/A	15,200	3,840	8,210- 9,240	(3,330)-(3,740)	510-100	0.06 - 0.01
	16 ft2/B	15,200	3,750	22,200	(8,990)	(5,240)	(0.2)
6. Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	4.5ft2/A	10,700	2,200	1,160- 1,440	(470)-(580)	1,730-1,610	1.5 - 1.1
	4.5ft2/B	10,700	2,300	5,550	(2,250)	50	0.01
	16 ft2/A	15,000	3,080	4,110- 5,130	(1,660)-(2,080)	1,420-1,000	0.4 - 0.2
	16 ft2/B	15,000	3,260	19,700	(7,990)	(4,730)	(0.2)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 6 hours idling; 2 hours working; 16 hours downtime; 5 days/week; 52 weeks/year

Schedule B: 4 hours idling; 12 hours working; 8 hours downtime; 5 days/week; 52 weeks/year

Table 5-8. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL OTVC's USING TRICHLOROTRIFLOUROETHANE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Automated Parts Handling System @11 fpm; Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,180	2,200	1,160- 1,440	(1,040)-(1,300)	1,160-900	1.0 - 0.6
	4.5ft2/B	8,180	2,770	3,470- 4,860	(3,120)-(4,370)	(350)-(1,600)	(0.1)-(0.3)
	16 ft2/A	15,200	3,630	4,110- 5,130	(3,700)-(4,620)	(60)-(990)	(0.02)-(0.2)
	16 ft2/B	15,200	4,200	12,300-17,300	(11,100)-(15,500)	(6,890)-(11,300)	(0.6)-(0.7)
2. Automated Parts Handling System @11 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,220	1,820	2,020- 2,310	(1,820)-(2,080)	0-(260)	0.0 -(0.1)
	4.5ft2/B	6,220	1,790	4,860- 5,550	(4,370)-(4,990)	(2,580)-(3,200)	(0.5)-(0.6)
	16 ft2/A	14,700	3,740	7,190- 8,210	(6,470)-(7,390)	(2,730)-(3,660)	(0.4)-(0.5)
	16 ft2/B	1,470	3,640	17,300-19,700	(15,500)-(17,800)	(11,900)-(14,100)	(0.7)-(0.7)
3. Automated Parts Handling System @11 fpm; Automated Bi-parting Cover	4.5ft2/A	10,200	2,090	870- 1,160	(780)-(1,040)	1,310-1,050	1.5 - 0.9
	4.5ft2/B	10,220	2,200	3,470- 4,160	(3,120)-(3,750)	(920)-(1,550)	(0.3)-(0.4)
	16 ft2/A	14,500	2,980	3,080- 4,110	(2,770)-(3,700)	210-(720)	0.1 -(0.2)
	16 ft2/B	14,500	3,160	12,300-14,800	(11,100)-(13,330)	(7,940)-(10,200)	(0.6)-(0.7)
4. Automated Parts Handling System @ 3 fpm Below-freezing FRD; 1.0 FBR	4.5ft2/A	8,680	2,300	1,440- 1,730	(1,300)-(1,560)	1,000-750	0.7 - 0.4
	4.5ft2/B	8,680	2,880	5,550	(4,990)	(2,120)	(0.4)
	16 ft2/B	15,700	3,740	5,130- 6,160	(4,620)-(5,540)	(890)-(1,810)	(0.2)-(0.3)
	16 ft2/B	15,700	4,310	19,700	(17,800)	(13,500)	(0.7)
5. Automated Parts Handling System @ 3 fpm; Enclosed Design; Sump Cooling	4.5ft2/A	6,720	1,920	2,310- 2,600	(2,080)-(2,340)	(160)-(420)	(0.1)-(0.2)
	4.5ft2/B	6,720	1,890	6,240	(5,620)	(3,730)	(0.6)
	16 ft2/A	15,200	3,840	8,210- 9,240	(7,390)-(8,320)	(3,560)-(4,480)	(0.4)-(0.5)
	16 ft2/B	15,200	3,750	22,200	(20,000)	(16,200)	(0.7)
6. Automated Parts Handling System @ 3 fpm; Automated Bi-parting Cover	4.5ft2/A	10,700	2,200	1,160- 1,440	(1,040)-(1,300)	1,160-900	1.0 - 0.6
	4.5ft2/B	10,700	2,300	5,550	(4,490)	(2,690)	(0.5)
	16 ft2/A	15,000	3,080	4,110- 5,130	(3,700)-(4,620)	(620)-(1,540)	(0.2)-(0.2)
	16 ft2/B	15,000	3,260	19,700	(17,800)	(14,500)	(0.7)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 6 hours idling; 2 hours working; 16 hours downtime; 5 days/week; 52 weeks/year

Schedule B: 4 hours idling; 12 hours working; 8 hours downtime; 5 days/week; 52 weeks/year

annualized costs. As a result, cost effectiveness values are lower for the higher priced solvents. The highest priced solvent, CFC-113, shows net annualized credits for a larger number of control options than with the other solvents. However, all solvents have credits for at least some options. For all control options and all solvents, the net annualized costs and cost effectiveness values are lower for OTVC's operating at Schedule B (where there is more working time and less idle time). This is due to the added emission reduction at no additional capital costs.

The option requiring an automated parts handling system operating at 3 fpm (through the vapor zone), an enclosed design, and sump cooling (Control Option 5) is generally the most cost-effective option for the small OTVC (Schedule A and B) and the large OTVC (Schedule A, only). The next most cost-effective control option is Control Option 2, which is identical to Control Option 5 except the speed of the automated parts handling system when parts are within the vapor zone is 11 fpm. In most instances, the two control options for these OTVC's with the highest cost effectiveness values include an automated parts handling system operating at 11 fpm and either a below-freezing freeboard refrigeration device and 1.0 FBR or a bi-parting cover (Control Options 1 and 3, respectively).

The ranking of the control options changes slightly for a large OTVC operating under Schedule B. It is noted that adding controls on these larger machines operating under a heavier working schedule produce annualized net credits in almost all instances, the exception being for Control Option 1 (and only then when the lower end of the control efficiency range is assumed). The highest net annualized credits for this model cleaner are for Control Option 5 (as with other OTVC models) and Control Option 6, the use of a bi-parting automated cover in addition to an automated parts handling system operating at 3 fpm through the vapor zone.

5.4 IN-LINE CLEANERS

5.4.1 Model Cleaner Parameters

In-line cleaners are generally greater than 20 ft^2 in the air/solvent vapor interface area and can be either vapor or cold cleaning operations. In order to examine the impacts of potential emission controls on both types of cleaners, a model cleaner with a solvent air interface of 38 ft^2 was selected. This model was used to represent both cold and vapor cleaners; the only in-line cold cleaners encountered during data gathering use MC in photoresist stripping operations. The model cleaner parameters for in-line cleaners are presented in Table 5-9. These parameters are based on industry contacts and EPA studies of the solvent cleaning industry. Two operating schedules were examined to evaluate the range of conditions that exist in the cold and vapor in-line cleaner market. There is no idling time in either in-line schedule. It is assumed that once the machine is turned on, parts will be continuously cycled through the machine until the end of the shift(s). If the continuous processing were not required, it is assumed solvent cleaner operators would choose the less expensive OTVC.

Uncontrolled emissions were calculated based on the amount of time the cleaner is operating and down. Uncontrolled emissions from the in-line model cleaner ranged from 47,100 lb/year under operating Schedule A to 114,000 lb/year under Schedule B.

TABLE 5-9. MODEL CLEANER PARAMETERS FOR IN-LINE CLEANERS

Parameter	In-Line - Schedule A					
Working area, ft^2	38.0					
Solvent	All					
Operating schedule hr/year						
Working	2080					
Downtime	6656					
Uncontrolled emission rates lb/hr						
Working	19					
Downtime	1.14					
Uncontrolled emissions[a] (lb/yr)						
Working	39520					
Downtime	7588					
Total	47100					
Control Option	1	2	3	4	5	6
Controlled emissions[b] (lb/yr) Total[c]	23600	23600	16500	16500	14100	14100
Emission Reduction	23600	23600	30600	30600	33000	33000

[a] Uncontrolled emissions based port covers in downtime.

[b] Controlled emissions based on the following:

	Efficiency (%)
Control Option 1: Below-freezing FRD	50
Control Option 2: Carbon Adsorber	50
Control Option 3: Below-freezing FRD; Sump Cooling	65
Control Option 4: Carbon Adsorption; Sump Cooling	65
Control Option 5: Super Heated Vapor; Sump Cooling	70
Control Option 6: Below-freezing FRD; Super Heated Vapor	70

NOTE: All reported efficiencies are for control of idling, working, and downtime losses only. They do not account for leaks, wastewater losses, or transfer losses which should be minimal if proper practices are employed.

FRD - Freeboard refrigeration devices
FBR - Freeboard ratio

TABLE 5-9. MODEL CLEANER PARAMETERS FOR IN-LINE CLEANERS (Continued)

Parameter				In-Line - Schedule B		
Working area, ft^2				38.0		
Solvent				All		
Operating schedule hr/year						
Working				5824		
Downtime				2912		
Uncontrolled emission rates lb/hr						
Working				19		
Downtime				1.14		
Uncontrolled emissions[a] (lb/yr)						
Working				111000		
Downtime				3320		
Total				114000		
Control Strategy	1	2	3	4	5	6
Controlled emissions[b] (lb/yr) Total[c]	45600	45600	45600	45600	17100	17100
Emission Reduction	68400	68400	68400	68400	96900	96900

[a] Uncontrolled emissions based on 0.75 FBR, port covers in downtime.

[b] Controlled emissions based on the following:

	Efficiency (%)
Control Option 1: Below-freezing FRD	60
Control Option 2: Carbon Adsorber	60
Control Option 3: Below-freezing FRD; Sump Cooling	60
Control Option 4: Carbon Adsorption; Sump Cooling	60
Control Option 5: Super Heated Vapor; Sump Cooling	85
Control Option 6: Below-freezing FRD; Super Heated Vapor	85

[c] Range based on range of Control Efficiencies

NOTE: All reported efficiencies are for control of idling, working, and downtime losses only. They do not account for leaks, wastewater losses, or transfer losses which should be minimal if proper practices are employed.

FRD - Freeboard refrigeration devices
FBR - Freeboard ratio

When calculating controlled emissions, no emission reduction or control cost was included for limiting the conveyor speed to 11 fpm since this is assumed to be occurring at baseline. The following five control options were considered as control alternatives:

- Control Option 1: a below-freezing freeboard refrigeration device;
- Control Option 2: a carbon adsorption system;
- Control Option 3: below-freezing freeboard refrigeration device and sump cooling;
- Control Option 4: a carbon adsorption system and sump cooling;
- Control Option 5: a super-heated vapor system and sump cooling; and
- Control Option 6: a below-freezing freeboard refrigeration device and super-heated vapor.

Due to the limited downtime in Schedule B, sump cooling has a relatively small effect on overall control efficiency. Therefore, only Control Options 1 through 3 and Control Option 6 are evaluated for this model.

Efficiencies were calculated based on existing test data. The efficiencies are summarized at the bottom of Table 5-9. Under Schedule A, Control Option 5 is the most effective, reducing total emissions by 70 percent. Under Schedule B, super-heated vapor (Control Option 3) reduces emissions by 70 percent, while the other controls reduce emissions by 60 percent.

5.4.2 Cost Evaluation

Table 5-10 presents the capital costs, annual operating costs, emission reduction, solvent recovery credit, net annualized costs, and cost effectiveness of retrofitting each of the control options on an in-line cleaner using MC. Tables 5-11 through 5-14 summarize this information for PCE, TCE, TCA, and CFC-113, respectively. The tables detailing these costs (and presenting the values for new in-lines) are presented in Appendix C-3.

As with OTVC's, the only variable among the calculations for each solvent was the solvent price (listed in Table 5-2). Therefore, the higher priced solvents have higher solvent recovery credits and, therefore, lower net annualized costs. As a result, cost effectiveness values are lower for the higher priced solvents. The highest priced solvent, CFC-113, shows net annualized credits for a larger number of control options than with the other solvents. For all control options and all solvents, the net annualized costs and cost effectiveness values are lowest for in-line cleaners operating under Schedule B. This effect is caused by achieving additional emission reduction under the longer operating schedule without incurring additional capital costs.

The addition of sump cooling during downtime has only a slight effect on cost effectiveness values of the same major control without sump cooling. In some cases, costs actually increase with the addition of sump cooling. All in-line control options, with the exception of a carbon adsorber (Control Option 2) always provided a net annualized credit. A credit for Control Option 2 only occurred for CFC-113 with Schedule B operation. The highest credit control for in-lines is the super-heated vapor system with sump cooling (Control Option 5).

Table 5-10. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL IN-LINE CLEANERS USING METHYLENE CHLORIDE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Below Freezing FRD	38 ft2/A	18,500	3,900	23,600	(6,100)	(2,200)	(0.1)
	38 ft2/B	18,500	5,200	68,400	(17,700)	(12,500)	(0.2)
2. Carbon Adsorber	38 ft2/A	80,500	23,600	23,600	(6,100)	17,500	0.7
	38 ft2/B	80,500	36,800	68,400	(17,700)	19,100	0.3
3. Below-freezing FRD; Sump Cooling	38 ft2/A	20,000	5,100	30,600	(9,490)	(2,830)	(0.2)
	38 ft2/B	20,000	6,210	68,400	(17,700)	(11,500)	(0.2)
4. Carbon Adsorber; Sump Cooling	38 ft2/A	82,000	25,000	30,600	(7,390)	17,000	0.6
	38 ft2/B	82,000	37,800	68,400	(17,700)	20,100	0.3
5. Super Heated Vapor; Sump Cooling	38 ft2/A	5,040	2,530	33,000	(8,540)	(6,020)	(0.2)
	38 ft2/B	5,040	3,640	96,900	(25,100)	(21,500)	(0.2)
6. Below-freezing FRD; Sump Cooling	38 ft2/A	22,100	5,230	33,000	(8,540)	(3,130)	(0.1)
	38 ft2/B	22,100	7,820	96,900	(25,100)	(17,300)	(0.2)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 8 hours working; 16 hours downtime; 5 days/week; 52 weeks/year

Schedule B: 16 hours working; 8 hours downtime; 7 days/week; 52 weeks/year

Table 5-11. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL IN-LINE CLEANERS USING PERCHLOROETHYLENE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Below Freezing FRD	38 ft2/A	18,500	3,900	23,600	(7,300)	(3,400)	(0.1)
	38 ft2/B	18,500	5,200	68,400	(21,200)	(16,000)	(0.2)
2. Carbon Adsorber	38 ft2/A	80,500	23,600	23,600	(7,300)	16,300	0.7
	38 ft2/B	80,500	36,800	68,400	(21,200)	15,600	0.2
3. Below-freezing FRD; Sump Cooling	38 ft2/A	20,000	5,100	30,600	(9,490)	(4,780)	(0.2)
	38 ft2/B	20,000	6,210	68,400	(21,200)	(15,000)	(0.2)
4. Carbon Adsorber; Sump Cooling	38 ft2/A	82,000	25,000	30,600	(9,490)	15,500	0.6
	38 ft2/B	82,000	37,800	68,400	(21,200)	16,600	0.2
5. Super Heated Vapor; Sump Cooling	38 ft2/A	5,040	2,530	33,000	(10,200)	(6,840)	(0.2)
	38 ft2/B	5,040	3,640	96,900	(30,000)	(26,400)	(0.3)
6. Below-freezing FRD; Sump Cooling	38 ft2/A	22,100	5,230	33,000	(10,200)	(4,990)	(0.2)
	38 ft2/B	22,100	7,820	96,900	(30,000)	(22,200)	(0.2)

FRD = freeboard refrigeration device
OPERATING SCHEDULES:
Schedule A: 8 hours working; 16 hours downtime; 5 days/week; 52 weeks/year
Schedule B: 16 hours working; 8 hours downtime; 7 days/week; 52 weeks/year

Table 5-12. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL IN-LINE CLEANERS USING TRICHLOROETHYLENE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Below Freezing FRD	38 ft2/A	18,500	3,900	23,600	(9,070)	(5,170)	(0.2)
	38 ft2/B	18,500	5,200	68,400	(26,300)	(21,100)	(0.3)
2. Carbon Adsorber	38 ft2/A	80,500	23,600	23,600	(9,070)	14,500	0.6
	38 ft2/B	80,500	36,800	68,400	(26,300)	10,500	0.2
3. Below-freezing FRD; Sump Cooling	38 ft2/A	20,000	5,100	30,600	(11,800)	(7,080)	(0.2)
	38 ft2/B	20,000	6,210	68,400	(26,300)	(20,100)	(0.3)
4. Carbon Adsorber; Sump Cooling	38 ft2/A	82,000	25,000	30,600	(11,800)	13,200	0.4
	38 ft2/B	82,000	37,800	68,400	(26,300)	11,500	0.2
5. Super Heated Vapor; Sump Cooling	38 ft2/A	5,040	2,530	33,000	(12,700)	(9,310)	(0.3)
	38 ft2/B	5,040	3,640	96,900	(37,300)	(33,700)	(0.4)
6. Below-freezing FRD; Sump Cooling	38 ft2/A	22,100	5,230	33,000	(12,700)	(7,470)	(0.2)
	38 ft2/B	22,100	7,820	96,900	(37,300)	(29,500)	(0.3)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 8 hours working; 16 hours downtime; 5 days/week; 52 weeks/year

Schedule B: 16 hours working; 8 hours downtime; 7 days/week; 52 weeks/year

Table 5-13. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL IN-LINE CLEANERS USING 1,1,1-TRICHLOROETHANE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Below Freezing FRD	38 ft2/A	18,500	3,900	23,600	(9,540)	(5,640)	(0.2)
	38 ft2/B	18,500	5,200	68,400	(27,700)	(22,500)	(0.3)
2. Carbon Adsorber	38 ft2/A	80,500	23,600	23,600	(9,540)	14,100	0.6
	38 ft2/B	80,500	36,800	68,400	(27,700)	9,090	0.1
3. Below-freezing FRD; Sump Cooling	38 ft2/A	20,000	5,100	30,600	(12,400)	(7,300)	(0.2)
	38 ft2/B	20,000	6,210	68,400	(27,700)	(21,500)	(0.3)
4. Carbon Adsorber; Sump Cooling	38 ft2/A	82,000	25,000	30,600	(12,400)	12,600	0.4
	38 ft2/B	82,000	37,800	68,400	(27,700)	10,100	0.2
5. Super Heated Vapor; Sump Cooling	38 ft2/A	5,040	2,530	33,000	(13,400)	(9,970)	(0.3)
	38 ft2/B	5,040	3,640	96,900	(39,200)	(35,600)	(0.9)
6. Below-freezing FRD; Sump Cooling	38 ft2/A	22,100	5,230	33,000	(13,400)	(8,130)	(0.2)
	38 ft2/B	22,100	7,820	96,900	(39,200)	(31,400)	(0.8)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 8 hours working; 16 hours downtime; 5 days/week; 52 weeks/year

Schedule B: 16 hours working; 8 hours downtime; 7 days/week; 52 weeks/year

Table 5-14. SUMMARY OF RETROFIT CONTROL COSTS AND COST EFFECTIVENESS FOR MODEL IN-LINE CLEANERS USING TRICHLOROTRIFLOUROETHANE (1988 $)

Control Option	Cleaner Size/ Operating Schedule	Total Installed Capital Cost ($)	Total Annualized Cost ($/yr)	Emission Reduction (lb/yr)	Recovered Solvent Credit ($/yr)	Net Annualized Cost ($/yr)	Cost Effectiveness ($/lb)
1. Below Freezing FRD	38 ft2/A	18,500	3,900	23,600	(21,200)	(17,300)	(0.7)
	38 ft2/B	18,500	5,200	68,400	(61,500)	(56,300)	(0.8)
2. Carbon Adsorber	38 ft2/A	80,500	23,600	23,600	(21,200)	2,400	0.1
	38 ft2/B	80,500	36,800	68,400	(61,500)	(24,800)	(0.4)
3. Below-freezing FRD; Sump Cooling	38 ft2/A	20,000	5,100	30,600	(27,690)	(22,500)	(0.7)
	38 ft2/B	20,000	6,210	68,400	(61,500)	(55,300)	(0.8)
4. Carbon Adsorber; Sump Cooling	38 ft2/A	82,000	25,000	30,600	(27,600)	(2,590)	(0.1)
	38 ft2/B	82,000	37,800	68,400	(61,500)	(23,700)	(0.4)
5. Super Heated Vapor; Sump Cooling	38 ft2/A	5,040	2,530	33,000	(29,700)	(26,300)	(0.8)
	38 ft2/B	5,040	3,640	96,900	(87,200)	(83,500)	(0.9)
6. Below-freezing FRD; Sump Cooling	38 ft2/A	22,100	5,230	33,000	(29,700)	(24,500)	(0.7)
	38 ft2/B	22,100	7,820	96,900	(87,200)	(79,400)	(0.8)

FRD = freeboard refrigeration device

OPERATING SCHEDULES:

Schedule A: 8 hours working; 16 hours downtime; 5 days/week; 52 weeks/year

Schedule B: 16 hours working; 8 hours downtime; 7 days/week; 52 weeks/year

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APPENDIX A

DERIVATION OF COMBINED EFFICIENCY FORMULA

APPENDIX A

The efficiencies for individual control techniques discussed in Chapter 4.0 are based on the single control technique being added to a solvent cleaner. When two or more control techniques act upon the same solvent emissions (i.e., idling, working), the combined efficiency of these techniques added to one cleaner is not equivalent to the direct sum of the individual efficiencies for each technique. The combined efficiency of two or more controls is somewhat less than the additive sum. This is because the additional techniques are essentially controlling only the emissions not already controlled by the first technique (i.e., the control techniques are essentially acting in series). The derivation of combined efficiency formulas for two control techniques and three control techniques, respectively, are described below.

Combined Efficiency Formula for Two Control Techniques

1. Let,

   B = baseline emissions (no control)
   E_1 = removal efficiency for control 1 only
   E_2 = removal efficiency for control 2 only

2. Then,

   BE_1 = amount of baseline emissions reduction using control 1

3. $B - BE_1$ = amount of baseline emissions remaining after application of control 1

4. $E_2(B - BE_1)$ = emission reduction control 2 acting on remaining emissions

5. Total Emission Reduction

$$= BE_1 + E_2(B - BE_1)$$
$$= BE_1 + BE_2 - BE_1E_2$$
$$= B[E_1 + E_2 - E_1E_2]$$

6. The effective removal efficiency (E_{EFF}) of control 1 and control 2 acting simultaneously on the baseline emissions (B) is, therefore,:

$$E_{EFF} = E_1 + E_2 - E_1E_2$$

Combined Efficiency formula for Three Control Techniques

1. Let,

   B = baseline emissions (no control)
   E_1 = removal percent for control 1 only
   E_2 = removal percent for control 2 only
   E_3 = removal percent for control 3 only

2. Then,

   BE_1 = amount of baseline emissions reduction using control 1

3. $B - BE_1$ = amount of emission remaining after application of control 1

4. $(B - BE_1)E_2$ = amount of emission reduction using control 2

5. $B - BE_1 - (BE_2 - BE_1E_2)$ = amount of emission remaining after application of control 2

6. $[B - BE_1 -(BE_2 - BE_1E_2)]E_3$ = amount of emission reduction using control 3

7. Total Emissions Reduction

$$= BE_1 + (B - BE_1)E_2 + [B - BE_1 -(BE_2 - BE_1E_2)]E_3$$

$$= BE_1 + BE_2 - BE_1E_2 + BE_3 - BE_1E_3 - BE_2E_3 + BE_1E_2E_3$$

$$= BE_1 + BE_2 + BE_3 - BE_1E_2 - BE_1E_3 - BE_2E_3 + BE_1E_2E_3$$

8. The effective removal efficiency (E_{EFF}) of controls 1, 2, and 3 acting on baseline emissions is:

$$E_{EFF} = E_1 + E_2 + E_3 - (E_1E_2) - (E_1E_3) - (E_2E_3) + (E_1E_2E_3)$$

The two combined efficiency formulas were used to calculate the efficiency of various OTVC and in-line cleaner control scenarios listed in Chapter 4 using the efficiency estimates for individual techniques. Table A-1 presents the range of efficiency for individual control techniques. These efficiency ranges were based on data in Tables 4-2 through 4-4 and reflect only those tests showing the effectiveness of control techniques on cleaners with the same characteristics as baseline conditions. It is assumed that a baseline OTVC has the following characteristics: (1) 0.75 FBR, (2) 70°F to 80°F primary condensing temperature for all solvents except MC and CFC, which have temperatures around 50°F to 60°F and (3) 100 fpm room air speed. A baseline in-line cleaner is assumed to have a 1.0 FBR. The control efficiencies listed in Table A-1 are intended to represent levels that can reasonably be expected under normal cleaner operating conditions.

Table A-2 presents the combined control efficiency for the OTVC and in-line cleaner control scenarios. An example calculation for OTVC control scenario (11 fpm hoist, freeboard refrigeration device - BF, 1.0 FBR) follows:

Idling Emissions

$E_1 + E_2 - (E_1E_2)$

$0.39 + 0.26 - (0.39 \times 0.26) = 55\%$ (lower end of range)

$0.39 + 0.58 - (0.39 \times 0.58) = 74\%$ (upper end of range)

Working Emissions

$E_1 + E_2 + E_3 - (E_1E_2) - (E_1E_3) - (E_2E_3) + (E_1E_2E_3)$

$0.28 + 0.19 + 0.28 - (0.28 \times 0.19) - (0.28 \times 0.28) - (0.19 \times 0.28) + (0.28 \times 0.19 \times 0.28) = 58\%$ (lower end of range)

$0.28 + 0.21 + 0.52 - (0.28 \times 0.21) - (0.28 \times 0.52) - (0.21 \times 0.52) + (0.28 \times 0.21 \times 0.52) = 73\%$ (upper end of range)

TABLE A-1. EFFECTIVENESS OF SOLVENT CLEANER CONTROL TECHNIQUES

	Achievable Emission Reduction Efficiency		
Control Techniques	Idling Emissions	Working Emissions	Downtime Emissions
OTVC			
o Hoist @ 11 fpm or less	-	28	-
o 1.0 FBR	39	19 - 21	-
o Automated cover	-	41 - 48	-
o Freeboard refrigeration device			
- Above freezing	-	16 - 50	-
- Below freezing	26 - 58	28 - 52	-
o Hoist @ 3 fpm or less	-	82	-
o 1.0 FBR	39	19 - 21	-
o Sump cooling device	-	-	90
o Carbon adsorption	-	65	-
o Enclosed design	-	42 - 67	-
In-Line Cleaners			
o Freeboard refrigeration device			
- Above freezing		8	-
- Below freezing		60	-
o Carbon adsorber		60	-
o Hot vapor recycle/ Superheated vapor		70	-
o Sump cooling device		-	90

TABLE A-2. EFFECTIVENESS OF SOLVENT CLEANER CONTROL TECHNIQUE SCENARIOS

	Control Efficiency Range (%)		
Control Techniques	Idling Emissions	Working Emissions	Downtime Emissions
OTVC			
o Hoist @ 11 fpm Freeboard refrigeration device (BF) 1.0 FBR	55 - 74	58 - 73	0
o Hoist @ 11 fpm ~~Encl~~osed design 2.0 FBR sump cooling	53 - 74	66 - 78	90
o Hoist @ 11 fpm Automated cover	41 - 48	57 - 62	0
o Hoist @ 3 fpm Freeboard refrigeration device (BF) 1.0 FBR	55 - 74	90	0
o Hoist @ 3 fpm Enclosed design 1.0 FBR sump cooling	53 - 74	91 - 95	90
o Hoist @ 3 fpm Automated cover	41 - 48	89 - 91	0
In-Line Cleaners			
o Freeboard refrigerationd evice (BF)	-	60	-
o Carbon adsorption	-	60	-
o Hot vapor recycle/ Superheated vapor	-	70	-
o Freeboard refrigeration device (BF) Sump cooling	-	60	90
o Hot vapor recycle/ Superheated vapor Sump cooling	-	70	90

APPENDIX B

OVERALL EFFICIENCY OF SELECTED CONTROL SCENARIOS

TABLE B-1. OVERALL EFFICIENCY OF OTVC CONTROL SCENARIOS UNDER SCHEDULE A[a]

Control Scenario[b]	Idling Emissions Reduction	% Total Emissions Due to Idling	Working Emissions Reduction (%)	% Total Emissions Due to Working	Downtime Emissions Reduction (%)	% Total Emissions Due to Downtime	Overall Emissions Reduction (%)
1	55 - 74	36	58 - 73	33	-	31	40 - 50
2	53 - 74[c]	36	68 - 78	33	90	31	70 - 80
3	41 - 48[c]	36	57 - 62	33	0	31	30 - 40
4	55 - 74	36	90	33	0	31	50 - 60
5	53 - 74[c]	36	91 - 95	33	90	31	80 - 90
6	41 - 48[c]	36	89 - 91	33	0	31	40 - 50

[a] Schedule A assumes: 6 hr/day idling, 2 hr/day working, and 16 hr/day downtime for 5 days/wk, 52 wks/yr; 24 hr/day downtime for 2 days/wk, 52 wks/yr.

[b] Control Scenario 1: Automated parts handling @ 11 fpm; Below-freezing FRD; 1.0 FBR
Control Scenario 2: Automated parts handling @ 11 fpm; Enclosed Design, Sump Cooling
Control Scenario 3: Automated parts handling @ 11 fpm; Automated Bi-parting Cover
Control Scenario 4: Automated parts handling @ 3 fpm; Below-freezing FRD; 1.0 FBR
Control Scenario 5: Automated parts handling @ 3 fpm; Enclosed Design; Sump Cooling
Control Scenario 6: Automated parts handling @ 3 fpm; Automated Bi-parting Cover

[c] Assumes that control efficiency is at least as good on idling emissions as it is on working emissions (where only working emissions control efficiency data are available).

TABLE B-2. OVERALL EFFICIENCY OF OTVC CONTROL SCENARIOS UNDER SCHEDULE B[a]

Control Scenario[b]	Idling Emissions Reduction	% Total Emissions Due to Idling	Working Emissions Reduction (%)	% Total Emissions Due to Working	Downtime Emissions Reduction (%)	% Total Emissions Due to Downtime	Overall Emissions Reduction (%)
1	55 - 74	10	58 - 73	81	-	9	50 - 70
2	53 - 74[c]	10	68 - 78	81	90	9	70 - 80
3	41 - 48[c]	10	57 - 62	81	0	9	50 - 60
4	55 - 74	10	90	81	0	9	80
5	53 - 74[c]	10	91 - 95	81	90	9	90
6	41 - 48[c]	10	89 - 91	81	0	9	80

[a] Schedule B assumes: 6 hr/day idling, 12 hr/day working, and 8 hr/day downtime for 5 days/wk, 52 wks/yr;
24 hr/day downtime for 2 days/wk, 52 wks/yr.

[b] Control Scenario 1: Automated parts handling @ 11 fpm; Below-freezing FRD; 1.0 FBR
Control Scenario 2: Automated parts handling @ 11 fpm; Enclosed Design, Sump Cooling
Control Scenario 3: Automated parts handling @ 11 fpm; Automated Bi-parting Cover
Control Scenario 4: Automated parts handling @ 3 fpm; Below-freezing FRD; 1.0 FBR
Control Scenario 5: Automated parts handling @ 3 fpm; Enclosed Design; Sump Cooling
Control Scenario 6: Automated parts handling @ 3 fpm; Automated Bi-parting Cover

[c] Assumes that control efficiency is at least as good on idling emissions as it is on working emissions (where only working emissions control efficiency data are available).

TABLE B-3. OVERALL EFFICIENCY OF IN-LINE CLEANER CONTROL SCENARIOS UNDER SCHEDULE A[a]

Control Scenario[b]	Working Emissions Reduction (%)	% Total Emissions Due to Working	Downtime Emissions Reduction (%)	% Total Emissions Due to Downtime	Overall Emissions Reduction (%)
1	60	84	-	16	50
2	60	84	-	16	50
3	70	84	-	16	60
4	60	84	90	16	65
5	70	84	90	16	70

[a] Schedule A assumes: 8 hr/day working and 16 hr/day downtime for 5 days/wk, 52 wks/yr; 24 hr/day downtime for 2 days/wk, 52 wks/yr.

[b] Control Scenario 1: Below-freezing FRD
Control Scenario 2: Carbon Adsorption
Control Scenario 3: Hot Vapor Recycle/Superheated Vapor
Control Scenario 4: Below-freezing FRD; Sump Cooling
Control Scenario 5: Hot Vapor Recycle/Superheated Vapor; Sump Cooling

TABLE B-4. OVERALL EFFICIENCY OF IN-LINE CLEANER CONTROL SCENARIOS UNDER SCHEDULE B[a]

Control Scenario[b]	Working Emissions Reduction (%)	% Total Emissions Due to Working	Downtime Emissions Reduction (%)	% Total Emissions Due to Downtime	Overall Emissions Reduction (%)
1	60	97	-	3	60
2	60	97	-	3	60
3	70	97	-	3	70
4	60	97	90	3	60
5	70	97	90	3	70

[a] Schedule B assumes: 16 hr/day working and 8 hr/day downtime for 365 days/yr.

[b] Control Scenario 1: Below-freezing FRD
Control Scenario 2: Carbon Adsorption
Control Scenario 3: Hot Vapor Recycle/Superheated Vapor
Control Scenario 4: Below-freezing FRD; Sump Cooling
Control Scenario 5: Hot Vapor Recycle/Superheated Vapor; Sump Cooling

APPENDIX C-1

DERIVATION OF CAPITAL COSTS

APPENDIX C-1 - DERIVATION OF CAPITAL COSTS

C-1.1 INTRODUCTION

Table C-1 provides a summary of the capital costs used in determining cost effectiveness for open top vapor, and in-line cleaners. The costs shown in the table represent fourth quarter 1988 costs and have been updated from the fourth quarter 1986 costs presented in the remainder of this appendix. When deriving capital costs, straight averages of vendor quotes were examined, but other considerations also affected cost choices (as discussed in Section 5.2.3). A detailed discussion of assumptions made in calculating specific capital costs for each degreaser follows. The sources of this information are discussed in Chapter 5.

Capital costs were annualized based on an annual percentage rate of 10 percent and the following equipment lifetimes based on vendor questionnaires:

OTVC:	10 years
In-line:	15 years

All controls except carbon adsorbers were assumed to have the same lifetime as the degreaser. A carbon adsorber has a reported lifetime of 10 years and was annualized over this life span.

C-1.2 OTVC's

Based on vendor quotations and the criteria detailed in Section 5.2.2 of the memorandum, the following base costs for OTVC's were selected:

4.5 ft^2:	$ 7,500
8.6 ft^2:	$10,000
16 ft^2:	$11,500
38 ft^2:	$16,000

Controls where more than one vendor quote was obtained are listed below, as well as methodology for selecting each cost.

TABLE C-1. CAPITAL COSTS (1988$)

	Total Installed Capital Costs ($)	
	New	Retrofit
Open Top Vapor Cleaners		
Very Small OTVC 4.5 ft^2		
Automated Parts Handling	1,500 - 2,000[a]	1,500 - 2,000
Below-freezing FRD	4,500	5,400
Above-freezing FRD	2,000	2,500
Bi-parting Cover	7,900	8,500
1.0 FBR	500	500
Carbon adsorber	28,400	29,500
Enclosed design	3,000	3,000
Sump Cooling	1,500	1,500
Small OTVC 8.5 ft^2		
Automated Parts Handling	1,500 - 2,000	1,500 - 2,000
Below-freezing FRD	7,600	9,100
Above-freezing FRD	6,000	7,300
Bi-parting Cover	9,100	10,200
1.0 FBR	500	500
Carbon adsorber	28,400	29,500
Enclosed design	5,000	5,000
Sump Cooling	1,500	1,500
Medium OTVC 16 ft^2		
Automated Parts Handling	3,000 - 3,500	3,000 - 3,500
Below-freezing FRD	8,600	10,300
Above-freezing FRD	7,400	8,800
Bi-parting Cover	10,200	11,300
1.0 FBR	600	600
Carbon adsorber	42,000	43,100
Enclosed design	10,000	10,000
Sump Cooling	1,500	1,500
Large OTVC 38 ft^2		
Automated Parts Handling	3,000 - 3,500	3,000 - 3,500
Below-freezing FRD	12 500	14,700
Above-freezing FRD	9,300	11,100
Bi-parting Cover	12,500	14,200
1.0 FBR	1,200	1,200
Carbon adsorber	51,000	52,100
Enclosed design		
Sump Cooling		

TABLE C-1. CAPITAL COSTS (1988$) (Continued)

	Total Installed Capital Costs ($)	
	New	Retrofit
In-line Cleaners 38 ft^2		
Below-freezing FRD	12 500	14,700
Above-freezing FRD	9,300	11,100
Carbon adsorber	61,000	75,000
Drying tunnel	6,000	6,000
Super heated vapor	3,000	3,000

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[a] All automated parts handling systems costs include a range. The lower cost is a push-button hoist capable of moving at a set speed. The higher cost is a push-button hoist capable of moving at two distinct speeds during the cycle.

C-1.2.1 Raising Freeboard Ratio from 0.75 To 1.0

All vendors currently selling OTVC's with a FBR of 0.75 provided cost estimates for raising the FBR to 1.0. With the exception of Phillips and Baron-Blakeslee, the costs included the cost to redesign the equipment; Phillips and Baron-Blakeslee's costs basically included the sheet metal enclosure. Although there may be some redesign cost, it is incurred only once and is spread out over all the units sold. Baron-Blakeslee indicated that the raised freeboard would be a prefabricated unit that would be easy to install. Since Phillips' costs were rough estimates and Baron-Blakeslee's costs were based on actual equipment they sell, it was decided that Baron-Blakeslee's costs were more reliable. The costs including redesign were not included since the redesign cost should only be incurred once for each model and not each time the 1.0 freeboard is requested. Below are Baron-Blakeslee's cost estimates.

Model Plant Size	Retrofit/New Costs For Increased FBR (.75 to 1.0)
4.5 ft^2	$ 400
8.6 ft^2	$ 450
16 ft^2	$ 550
38 ft^2	$1,100

C-1.2.2 Covers

C-1.2.2.1 Manual/Mechanically-assisted. All vendors include at least a manual cover on all degreasers. Detrex and Baron-Blakeslee include mechanically assisted covers on all degreasers. It was assumed that, at baseline, all OTVC's have manual covers.

C-1.2.2.2 Power Covers. One of the vendors providing power cover costs (Branson) does not manufacture power covers, nor have they retrofitted another manufacturers' cover on a regular basis. Their costs were "best guesses" and were eliminated from consideration. The following information was also obtained from vendor correspondence:

- Unique and Phillips' power covers are mylar roll up covers. Westinghouse's power cover is a rigid steel top with hinges at the back.

- According to Phillips a steel roll up cover would cost roughly 3 times the mylar cover.

- Baron Blakeslee's power cover is a steel roll up cover. Baron-Blakeslee's power cover costs are slightly more than 2 times the mylar equivalent covers for the $0.4m^2$ and $0.8m^2$ degreasers. This estimate supports Phillips' estimate mentioned above.

- None of the above covers are capable of being closed during degreaser operation. A cover capable of this is a bi-parting cover.

- Baron Blakeslee estimates that a bi-parting cover would cost about 2 times the cost of a steel roll up cover.

- Detrex estimates that a bi-parting cover would cost 120 to 133% of their power cover listed.

Cost Estimate Approach

- For the 4.5 and 8.6 ft^2 degreasers, 6 times the mylar cover cost and 2 times the Baron-Blakeslee costs were examined. These values should approximate the costs of bi-parting steel covers based on the Phillips estimate that a steel rollup cover costs 3 times a mylar cover, and Baron Blakeslee's estimate that a bi-parting cover costs

2 times a steel rollup cover. The following values were obtained.

Degreaser Size	6x "Mylar Equivalent"		2x Baron-Blakeslee[*]
	New	Retrofit	
4.5 ft^2	8,800	10,000	7,000
8.6 ft^2	8,500	11,200	8,000

- For the 1.5m^2 and 3.5m^2 degreasers, the Detrex estimates were also available (though confidential):

Degreaser Size	6x "Mylar Equivalent"		2x Baron-Blakeslee[*]
	New	Retrofit	
16 ft^2	8,600	12,300	12,000
38 ft^2	6,700	15,900	15,000

Based on the above information the following costs were selected:

Degreaser Size	Rationale:
4.5 ft^2 New - $ 7000 Ret - $ 7500	Based on twice the Baron-Blakeslee cost. There is only one "mylar equivalent" supplier in this range (Unique) and Baron-Blakeslee is a much larger vendor. Although Baron-Blakeslee has no retrofit cost increase for a power cover, it was acknowledged that other manufacturers do.
8.6 ft^2 New - $ 8,000 Ret - $ 9,000	These costs were selected based on the criteria listed in Section 2.0.

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[*] Baron-Blakeslee's rollup cover is self contained and simply attaches to degreaser, therefore there is no increase to retrofit. There is no estimate available as to how this would differ for a bi-parting cover.

16 ft^2

New - \$ 9,000
Ret - \$10,000

The lower "mylar equivalent" costs (as opposed to the smaller cleaners) are due to only Phillips supplying costs for covers in these size ranges. Selected costs are based on the cost presented above and consideration of Detrex's costs. Engineering judgement was used to adjust costs to ensure that these sizes do not cost less than smaller sizes.

38 ft^2

New - \$11,000
Ret - \$12,500

C-1.2.3 Refrigerated Freeboard Chillers

The following above freezing (AF) and below freezing (BF) chiller costs were eliminated from consideration because the vendors do not manufacture the units and have not purchased a significant amount from other vendors to retrofit to their equipment:

Branson	- AF & BF
Unique	- BF
Westinghouse	- AF on 16 ft^2 only

The following costs are recommended based on the basic criteria listed in Section 2.0 of the memorandum.

	AF Chiller		BF Chiller	
Degreaser Size	New	Ret	New	Ret
4.5 ft^2	\$1,800	2,200	4,000	4,800
8.6 ft^2	5,300	6,400	6,700	8,000
16 ft^2	6,500	7,800	7,600	9,100
38 ft^2	8,200	9,800	11,000	13,000

The costs for new chillers were based on vendor quotes. Retrofit costs for the chillers were not provided by all vendors. The costs that were provided ranged from no increase over new costs to 100% increases. The larger vendors, Baron-Blakeslee and Detrex, had lower percent increases. It was decided to pick a consistent increase of 20 percent for retrofitting all chillers.

C-1.2.4 Carbon Adsorbers

Three of the responding OTVC vendors (Baron-Blakeslee, Detrex, and Phillips) manufacture carbon adsorbers. These vendors supplied carbon adsorber costs only for the size OTVC's their company sells. The costs they provided ranged widely for comparable size OTVC's. Because taking a simple average of the reported data yielded inconsistencies (i.e., costs for small OTVC's were higher than for large OTVC's), the cost data from each vendor was extrapolated over the entire range of OTVC sizes. This adjustment was made to ensure a logical progression of costs.

Information provided on retrofit costs was very limited. The information available indicated there is a small increase in cost for retrofitting a carbon adsorber. The retrofit costs are associated with retrofitting the lip exhaust. For estimating retrofit costs, $1,000 was added to the new cost for each model OTVC. The new and retrofit carbon adsorber costs are shown below.

OTVC Size	New Cost	Retrofit Cost
4.5 ft^2, 8.6 ft^2	$25,000	$26,000
16 ft^2	$37,000	$38,000
38 ft^2	$45,000	$46,000

C-1.2.5 Automated Parts Handling Systems

The following quotes were obtained for automated parts handling systems. It should be noted that hoist costs were dependent on features and not necessarily the size of the OTVC.

Responder	System Cost ($)	Comments
Baron-Blakeslee	10,000	programmable, 50 lb
Baron-Blakeslee	16,000	programmable, 200 lb
Scanex	4,500 - 5,000	variable speed, Model E
Scanex	12,000	variable speed and position, Model R
Scanex	18,000 - 25,000	variable speed, acceleration, Model S
Phillips	10,000	programmable, 100 lb
Phillips	30,000	programmable, 200 lb
Detrex	15,000	programmable, 12 lb
Detrex	25,000	programmable, 50 lb
Unique	7,500	variable speed, 50 lb
Delta Sonics	1,500 - 2,000	1 direction, 1 & 2 speed, 30 lb
Delta Sonics	3,000 - 3,500	1 direction, 1 & 2 speed, 100-200 lb

Although more elaborate and expensive controls can be used, the cost analysis should include the minimum, reasonable control that can be used to meet a requirement. For this reson, Delta Sonics' hoists were assumed to meet the minimum requirement. The lower costs in the ranges are for a one-directional hoist capable of moving up and down at a set speed. The higher prices are for a hoist capable of switching from 11 fpm to 3 fpm when a part enters the vapor zoen and then back to 11 fpm once the part has come back through the zone. These hoists would be push button operated.

	Costs ($)	
OTVC Size	Control Strategies 1 - 3	Control Strategies 4 - 6
4.5 ft^2	1,500	2,000
16 ft^2	3,000	3,500

C-1.3 IN-LINE

Three companies provided costs for in-line cleaners (CC) having the following sizes:

Unique:	13 ft^2
Detrex:	14 ft^2
Baron-Blakeslee:	24 ft^2 (crossrod)
Baron-Blakeslee:	72 ft^2 (monorail)

All of the above cleaners were used to calculate costs for the 38 ft^2 model cleaner. When recommending costs, average values were used as a guide, but not strictly adhered to. Based on the vendor quotations, a base cost of $60,000 was selected.

C-1.3.1 Freeboard Refrigeration Devices

The only cost data provided for above freezing (AF) freeboard refrigeration devices is from Unique Industries. They provided a new cost of $8,000 and did not report retrofit data. The non-confidential costs provided by the CC vendors for below freezing (BF) freeboard refrigeration devices were:

CC Size	New Cost
13 ft^2	$12,000
24 ft^2	$12,500
72 ft^2	$20,000

Based on these cost estimates and the Detrex confidential cost estimate, a value of 13,000 was selected for the new cost of a BF chiller. For retrofit costs it was decided that a consistent increase of 20 percent over new device costs should be used. [This approach was also taken in estimating the retrofit control costs for OTVC's.] The new and retrofit costs are shown below:

	New	Retrofit
AF	8,000	9,600
BF	13,000	15,600

Carbon Adsorbers

Vendor quotes for carbon adsorbers have the following ranges:

New -	$40,000 - $100,000
Retrofit -	$66,000 - $100,000

The $100,000 quotes are from Unique who has previously stated that they do not make carbon adsorbers. The following values were selected using Blakeslee's costs with some adjustment to take information from Detrex into account.

New -	54,000
Retrofit -	66,000

APPENDIX C-2

DERIVATION OF ANNUAL COSTS

APPENDIX C

Actual costs incurred by individual plants in the operation of solvent cleaners will vary. Table C-2 contains operating requirements which are typical and should provide a reasonable estimate of operating costs. The values were obtained from vendor questionnaires and follow-up correspondence. The estimates from the vendors were evaluated based on similar criteria to those used for the capital costs.

TABLE C-2. OPERATING PARAMETERS USED IN COST ANALYSIS

	Electricity (hp)	Added Floor Space (ft^2)	Added Operator Labor (hrs/shift)	Steam (lb/lb pollutant)	Cooling Water (gal/100 lb Steam)
4.5ft^2 OTVC					
Hoist	.2	4	-	-	-
Below-freezing FRD	1.5	6	.1	-	-
Bi-parting cover	.5	-	-	-	-
1.0 FBR	-	-	-	-	-
Enclosed design	-	-	-	-	-
Sump cooling	.5	-	.1	-	-
16.0ft^2 OTVC					
Hoist	.2	4	-	-	-
Below-freezing FRD	1.5	10	.1	-	-
Bi-parting cover	1	-	-	-	-
1.0 FBR	1	10	.1	-	-
Enclosed design	-	-	-	-	-
Sump cooling	1	-	.1	-	-
38.0ft^2 In-line					
Below-freezing FRD	3	15	.1	-	-
Carbon adsorber	6	100	.5	4	12
Drying tunnel	-	10	-	-	-
Super-heated vapor	3	0	.1	-	-
Sump Cooling	1.5	0	.1	-	-

CALCULATION OF OPERATING COSTS

The following equations were used along with values taken from Tables 5-6 and C-2 to obtain the annual operating costs. It should be noted that operating labor costs were considered for all control techniques. However, supervisory and maintenance labor, maintenance material, and overhead were only included for carbon adsorbers since this is the only control technique that would require a significant amount of added labor and maintenance.

1. OPERATING LABOR

Labor rates from 1977 were updated to 4th quarter 1986 using the BLS Producer Price Index. Shifts per year were obtained from model plant parameters. Manhours per shift were given in Table C-2.

$$OL = Shifts \times Payrate \times Hours$$

Where OL = Operating Labor, ($/yr)
Shifts = Shifts per year
Payrate = $/hr in 1988 dollars
Hours = Hours of labor per shift.

2. SUPERVISOR LABOR (FOR CARBON ADSORBERS ONLY)

Supervisor labor is estimated at 15 percent of operator labor cost

$$SL = 0.15 \times OL$$

Where SL = Supervisor Labor, ($/yr)

3. MAINTENANCE LABOR

Maintenance labor is based on .5 manhours per shift.

ML = Shifts x Payrate x Hours

Where ML = Maintenance
(Remainder same nomenclature as Operating Labor)

4. MAINTENANCE MATERIALS (FOR CARBON ADSORBERS ONLY)

Materials necessary for maintenance are estimated as being equivalent to maintenance labor costs.

MM = ML

Where MM = Maintenance Material Costs, ($/yr)

5. OVERHEAD (FOR CARBON ADSORBERS ONLY)

Overhead is estimated at 60% of Labor Costs and Maintenance Materials.

OH = .6 (OL + ML + SL + MM)

Where OH = Overhead Costs, ($/yr)

6. MISCELLANEOUS OPERATING COSTS

Includes property tax, insurance, and administration costs. Is estimated at 4 percent of Total Capital Costs.

MOC = 0.04 x (Total Capital Costs)

Where MOC = Miscellaneous Operating Costs

7. UTILITY COSTS

Annual costs for electricity, steam, and cooling water (where applicable) were calculated according to the following equations:

Electricity Cost = hp x 0.746 kw/hp x hrs/yr x EP

Where hp = horsepower requirements
EP = electricity price ($/kwh) in 1988 dollars

Steam Cost = SR x POLL x SP

Where SR = steam requirements (per amount pollutant recovered)
POLL = lbs pollutant recovered per year
SP = steam price ($/lb) in 1988 dollars

Cooling
Water Cost = CWR x POLL x CWP

Where CWR = cooling water requirements (per lb of recovered pollutant)
POLL = lb pollutant recovered per year
CWP = cooling water price ($/gal) in 1988 dollars

8. ADDED PLANT SPACE COSTS

The added plant space costs are calculated as shown below and added to the capital costs of control prior to annualization of the capital costs.

PS = Space x SCost

Where PS = Plant Space, $.
Space = Space Requirements, ft^2 of floor area
SCost = Floor Space Cost, $\$/ft^2$

9. NET ANNUALIZED COSTS

Net annualized costs include annualized capital costs, annual operating cost and credit for recovered solvent. Capital cost is annualized according to the following equation.

AC = Total Capital x Capital Recovery Factor

Where Capital Recovery Factor is calculated for 10 percent discount rate and the following equipment life times:

All cold cleaner controls - 10 years, CFR = .1627

All OTVC controls - 10 years, CFR = .1627

In-line degreaser controls except carbon adsorbers - 15 years, CFR = .1315

Carbon adsorbers on in-line degreasers - 10 years, CFR = .1627

SAMPLE CALCULATION (These are in 1986 $)

The Operating Costs required for a carbon adsorber added on a 38 ft^2 Open Top Vapor Cleaner are shown.

1. OPERATOR LABOR

$$OL = Shifts \times Payrate \times Hours$$

$$= 250 \, \frac{Shifts}{year} \times 7.98 \, \frac{309.5}{194.7} \, \frac{\$}{hour} \times .5 \, \frac{hours}{shift}$$

$$= \$1,563.79/yr$$

2. SUPERVISOR LABOR

$$SL = 0.15 \; (1563.79 \; \$/yr) = \$234.57/yr$$

3. MAINTENANCE LABOR

The calculation is the same as with operator labor, but maintenance labor rates are used.

$$ML = 250 \, \frac{Shifts}{year} \times 8.66 \, \frac{309.5}{194.7} \, \frac{\$}{hour} \times .5 \, \frac{hours}{shift}$$

$$= \$1,720.77/yr$$

4. MAINTENANCE MATERIALS

Equal to Maintenance Labor, \$1,720.77/yr

5. **OVERHEAD**

$$OH = .6\,(1{,}563.79 + 234.57 + 1{,}720.77 + 1{,}720.77)$$

$$= \$3{,}143.94/\text{yr}$$

6. **MISCELLANEOUS OPERATING COSTS**

$$MOC = 0.04 \times 51{,}220 = 2{,}048.80$$

7. **ANNUALIZED COSTS**

Since the carbon adsorber life is ten years, .1627

$$AC = .1314 \times 51{,}220 = 8{,}333.49$$

Calculational methods for electricity, cooling water, and steam are also shown.

ELECTRICITY: a 6 hp fan is to be used.

$$6\ \text{hp} \times \frac{1\ \text{kw}}{1.34102\ \text{hp}} \times 1500\ \text{hrs/yr} \times \$.0713/\text{kwhr}$$

$$= \$478.52/\text{yr}$$

STEAM: From the Gard Manual, it takes 4 pounds of steam to recover 1 pound of pollutant from the carbon bed. The emission reduction is estimated to be 10,661 pounds/year (4,836 kg/yr) at 52 percent control efficiency

$$\frac{4\ \text{lbs steam}}{1\ \text{lb pollutant}} \times \frac{10{,}661\ \text{lbs}}{\text{year}} \times \frac{\$5.39}{1{,}000\ \text{lbs steam}} = \$229.85/\text{year}$$

COOLING WATER: It is reported that it takes 12 gallons per 100 lbs of steam (or 12 gallons per 25 pounds pollutant recovered).

$$\frac{12\text{ gallons}}{25\text{ lbs pollutant}} \times \frac{10{,}661\text{ lbs}}{\text{year}} - \frac{\$0.087}{1{,}000\text{ gallons}} = \$0.44$$

Since it will take 100 square feet to install the adsorber,

$$\text{Plant Space costs} = 100\text{ ft}^2 \times \$42\ \frac{304.4}{244.7} = \$5{,}224.68$$

APPENDIX C-3

COST EFFECTIVENESS CALCULATION TABLES

06-Apr-89

Small OTVC (4.5 ft2)-Schedule A (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	1,500	1,500	1,500	2,000	2,000	2,000
Below-freezing FRD	5,400	0	0	5,400	0	0
Bi-parting cover	0	0	8,500	0	0	8,500
1.0 FBR	500	0	0	500	0	0
Enclosed Design	0	3,000	0	0	3,000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	780	223	223	780	223	223
TOTAL CAPITAL COSTS	8,180	6,223	10,223	8,680	6,723	10,723
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	1,331	1,012	1,663	1,412	1,094	1,745
Operating labor	358	358	0	358	358	0
Utilities						
Electricity	188	200	21	188	200	21
Miscellaneous operating costs	327	249	409	347	269	429
TOTAL ANNUALIZED COST, $/yr	2,204	1,819	2,093	2,306	1,921	2,195
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	1,155 - 1,444	2,022 - 2,310	866 - 1,155	1,444 - 1,733	2,310 - 2,599	1,155 - 1,444
RECOVERED SOLVENT CREDIT, $/yr						
MC	(299) - (374)	(524) - (598)	(224) - (299)	(374) - (449)	(598) - (673)	(299) - (374)
PCE	(358) - (448)	(627) - (716)	(269) - (358)	(448) - (537)	(716) - (806)	(358) - (448)
TCE	(445) - (556)	(778) - (890)	(334) - (445)	(556) - (667)	(890) - (1,001)	(445) - (556)
TCA	(468) - (585)	(819) - (936)	(351) - (468)	(585) - (702)	(936) - (1,053)	(468) - (585)
CFC-113	(1,040) - (1,300)	(1,819) - (2,079)	(780) - (1,040)	(1,300) - (1,560)	(2,079) - (2,339)	(1,040) - (1,300)
NET ANNUALIZED COSTS, $/yr						
MC	1,905 - 1,830	1,296 - 1,221	1,869 - 1,794	1,932 - 1,857	1,322 - 1,248	1,895 - 1,821
PCE	1,846 - 1,757	1,193 - 1,103	1,825 - 1,735	1,858 - 1,769	1,205 - 1,115	1,836 - 1,747
TCE	1,760 - 1,648	1,041 - 930	1,760 - 1,648	1,750 - 1,639	1,031 - 920	1,750 - 1,639
TCA	1,737 - 1,620	1,001 - 884	1,742 - 1,625	1,721 - 1,604	985 - 868	1,727 - 1,610
CFC-113	1,165 - 905	0 - (260)	1,313 - 1,054	1,006 - 746	(159) - (418)	1,155 - 895

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Small OTVC (4.5 ft2)-Schedule A (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
COST EFFECTIVENESS, $/lb						
MC	1.65 - 1.27	0.64 - 0.53	2.16 - 1.55	1.34 - 1.07	0.57 - 0.48	1.64 - 1.26
PCE	1.60 - 1.22	0.59 - 0.48	2.11 - 1.50	1.29 - 1.02	0.52 - 0.43	1.59 - 1.21
TCE	1.52 - 1.14	0.52 - 0.40	2.03 - 1.43	1.21 - 0.95	0.45 - 0.35	1.51 - 1.13
TCA	1.50 - 1.12	0.50 - 0.38	2.01 - 1.41	1.19 - 0.93	0.43 - 0.33	1.49 - 1.11
CFC-113	1.01 - 0.63	0.00 - (0.11)	1.52 - 0.91	0.70 - 0.43	(0.07) - (0.16)	1.00 - 0.62

Control Strategy 1: Hoist at 11 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

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Small OTVC (4.5 ft2)-Schedule B (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	1,500	1,500	1,500	2,000	2,000	2,000
Below-freezing FRD	5,400	0	0	5,400	0	0
Bi-parting cover	0	0	8,500	0	0	8,500
1.0 FBR	500	0	0	500	0	0
Enclosed Design	0	3,000	0	0	3,000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	780	223	223	780	223	223
TOTAL CAPITAL COSTS	8,180	6,223	10,223	8,680	6,723	10,723
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	1,331	1,012	1,663	1,412	1,094	1,745
Operating labor	717	358	0	717	358	0
Utilities						
Electricity	400	170	127	400	170	127
Miscellaneous operating costs	327	249	409	347	269	429
TOTAL ANNUALIZED COST, $/yr	2,774	1,789	2,199	2,876	1,891	2,301
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	3,468 - 4,855	4,855 - 5,549	3,468 - 4,162	5,549 - 5,549	6,242 - 6,242	5,549 - 5,549
RECOVERED SOLVENT CREDIT, $/yr						
MC	(898) - (1,257)	(1,257) - (1,437)	(898) - (1,078)	(1,437) - (1,437)	(1,617) - (1,617)	(1,437) - (1,437)
PCE	(1,075) - (1,505)	(1,505) - (1,720)	(1,075) - (1,290)	(1,720) - (1,720)	(1,935) - (1,935)	(1,720) - (1,720)
TCE	(1,335) - (1,869)	(1,869) - (2,136)	(1,335) - (1,602)	(2,136) - (2,136)	(2,403) - (2,403)	(2,136) - (2,136)
TCA	(1,405) - (1,966)	(1,966) - (2,247)	(1,405) - (1,686)	(2,247) - (2,247)	(2,528) - (2,528)	(2,247) - (2,247)
CFC-113	(3,121) - (4,370)	(4,370) - (4,994)	(3,121) - (3,746)	(4,994) - (4,994)	(5,618) - (5,618)	(4,994) - (4,994)
NET ANNUALIZED COSTS, $/yr						
MC	1,876 - 1,517	532 - 352	1,301 - 1,121	1,438 - 1,438	274 - 274	864 - 864
PCE	1,699 - 1,269	284 - 69	1,124 - 909	1,155 - 1,155	(45) - (45)	581 - 581
TCE	1,439 - 905	(80) - (347)	864 - 597	739 - 739	(513) - (513)	164 - 164
TCA	1,370 - 808	(177) - (458)	795 - 514	628 - 628	(638) - (638)	53 - 53
CFC-113	(347) - (1,595)	(2,580) - (3,205)	(922) - (1,546)	(2,118) - (2,119)	(3,728) - (3,728)	(2,698) - (2,698)

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Small OTVC (4.5 ft2)-Schedule B (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
COST EFFECTIVENESS, $/lb						
MC	0.54 - 0.31	0.11 - 0.06	0.38 - 0.27	0.26 - 0.26	0.04 - 0.04	0.16 - 0.16
PCE	0.49 - 0.26	0.06 - 0.01	0.32 - 0.22	0.21 - 0.21	(0.01) - (0.01)	0.10 - 0.10
TCE	0.41 - 0.19	(0.02) - (0.06)	0.25 - 0.14	0.13 - 0.13	(0.08) - (0.08)	0.03 - 0.03
TCA	0.39 - 0.17	(0.04) - (0.08)	0.23 - 0.12	0.11 - 0.11	(0.10) - (0.10)	0.01 - 0.01
CFC-113	(0.10) - (0.33)	(0.53) - (0.58)	(0.27) - (0.37)	(0.38) - (0.38)	(0.60) - (0.60)	(0.49) - (0.49)

Control Strategy 1: Hoist at 11 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

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Large OTVC (16.0 ft2)-Schedule A (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	3,000	3,000	3,000	3,500	3,500	3,500
Below-freezing FRD	10,300	0	0	10,300	0	0
Bi-parting cover	0	0	11,300	0	0	11,300
1.0 FBR	600	0	0	600	0	0
Enclosed Design	0	10,000	0	0	10,000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	1,336	223	223	1,336	223	223
TOTAL CAPITAL COSTS	15,236	14,723	14,523	15,736	15,223	15,023
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,479	2,395	2,363	2,560	2,477	2,444
Operating labor	358	358	0	358	358	0
Utilities						
Electricity	188	393	36	188	393	36
Miscellaneous operating costs	609	589	581	629	609	601
TOTAL ANNUALIZED COST, $/yr	3,634	3,736	2,980	3,736	3,837	3,081
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	4,107 - 5,134	7,187 - 8,214	3,080 - 4,107	5,134 - 6,160	8,214 - 9,240	4,107 - 5,134
RECOVERED SOLVENT CREDIT, $/yr						
MC	(1,064) - (1,330)	(1,861) - (2,127)	(798) - (1,064)	(1,330) - (1,595)	(2,127) - (2,393)	(1,064) - (1,330)
PCE	(1,273) - (1,592)	(2,228) - (2,546)	(955) - (1,273)	(1,591) - (1,910)	(2,546) - (2,864)	(1,273) - (1,591)
TCE	(1,581) - (1,977)	(2,767) - (3,162)	(1,186) - (1,581)	(1,976) - (2,372)	(3,162) - (3,558)	(1,581) - (1,976)
TCA	(1,663) - (2,079)	(2,911) - (3,327)	(1,247) - (1,663)	(2,079) - (2,495)	(3,327) - (3,742)	(1,663) - (2,079)
CFC-113	(3,696) - (4,621)	(6,468) - (7,392)	(2,772) - (3,696)	(4,620) - (5,544)	(7,392) - (8,316)	(3,696) - (4,620)
NET ANNUALIZED COSTS, $/yr						
MC	2,571 - 2,305	1,875 - 1,609	2,182 - 1,916	2,406 - 2,140	1,710 - 1,444	2,018 - 1,752
PCE	2,361 - 2,043	1,508 - 1,190	2,025 - 1,707	2,144 - 1,826	1,291 - 973	1,808 - 1,490
TCE	2,053 - 1,658	969 - 574	1,794 - 1,399	1,759 - 1,364	675 - 280	1,500 - 1,105
TCA	1,971 - 1,555	825 - 410	1,733 - 1,317	1,657 - 1,241	511 - 95	1,418 - 1,002
CFC-113	(62) - (986)	(2,732) - (3,656)	208 - (716)	(885) - (1,809)	(3,555) - (4,479)	(615) - (1,539)

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Large OTVC (16.0 ft2)-Schedule A (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
COST EFFECTIVENESS, $/lb						
MC	0.63 - 0.45	0.26 - 0.20	0.71 - 0.47	0.47 - 0.35	0.21 - 0.16	0.49 - 0.34
FCE	0.57 - 0.40	0.21 - 0.14	0.66 - 0.42	0.42 - 0.30	0.16 - 0.11	0.44 - 0.29
TCE	0.50 - 0.32	0.13 - 0.07	0.58 - 0.34	0.34 - 0.22	0.08 - 0.03	0.37 - 0.22
TCA	0.48 - 0.30	0.11 - 0.05	0.56 - 0.32	0.32 - 0.20	0.06 - 0.01	0.35 - 0.20
CFC-113	(0.02) - (0.19)	(0.38) - (0.45)	0.07 - (0.17)	(0.17) - (0.29)	(0.43) - (0.48)	(0.15) - (0.30)

Control Strategy 1: Hoist at 11 fpm, Below-freezong FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

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Large OTVC (16.0 ft2)-Schedule B (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	3,000	3,000	3,000	3,500	3,500	3,500
Below-freezing FRD	10,300	0	0	10,300	0	0
Bi-parting cover	0	0	11,300	0	0	11,300
1.0 FBR	600	0	0	600	0	0
Enclosed Design	0	10,000	0	0	10,000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	1,336	223	223	1,336	223	223
TOTAL CAPITAL COSTS	15,236	14,723	14,523	15,736	15,223	15,023
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,479	2,395	2,363	2,560	2,477	2,444
Operating labor	717	358	0	717	358	0
Utilities						
Electricity	400	303	218	400	303	218
Miscellaneous operating costs	609	589	581	629	609	601
TOTAL ANNUALIZED COST, $/yr	4,204	3,645	3,162	4,306	3,747	3,263
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	12,330 - 17,262	17,262 - 19,728	12,330 - 14,796	19,728 - 19,728	22,194 - 22,194	19,728 - 19,728
RECOVERED SOLVENT CREDIT, $/yr						
MC	(3,193) - (4,471)	(4,471) - (5,110)	(3,193) - (3,832)	(5,110) - (5,110)	(5,748) - (5,748)	(5,110) - (5,110)
PCE	(3,822) - (5,351)	(5,351) - (6,116)	(3,822) - (4,587)	(6,116) - (6,116)	(6,880) - (6,880)	(6,116) - (6,116)
TCE	(4,747) - (6,646)	(6,646) - (7,595)	(4,747) - (5,696)	(7,595) - (7,595)	(8,545) - (8,545)	(7,595) - (7,595)
TCA	(4,994) - (6,991)	(6,991) - (7,990)	(4,994) - (5,992)	(7,990) - (7,990)	(8,989) - (8,989)	(7,990) - (7,990)
CFC-113	(11,097) - (15,536)	(15,536) - (17,755)	(11,097) - (13,316)	(17,755) - (17,755)	(19,975) - (19,975)	(17,755) - (17,755)
NET ANNUALIZED COSTS, $/yr						
MC	1,011 - (266)	(826) - (1,464)	(32) - (670)	(804) - (804)	(2,002) - (2,002)	(1,846) - (1,846)
PCE	382 - (1,147)	(1,706) - (2,470)	(661) - (1,425)	(1,810) - (1,810)	(3,134) - (3,134)	(2,853) - (2,853)
TCE	(543) - (2,441)	(3,001) - (3,950)	(1,585) - (2,535)	(3,290) - (3,290)	(4,798) - (4,798)	(4,332) - (4,332)
TCA	(789) - (2,787)	(3,346) - (4,345)	(1,832) - (2,831)	(3,684) - (3,684)	(5,242) - (5,242)	(4,727) - (4,727)
CFC-113	(6,898) - (11,331)	(11,891) - (14,110)	(7,935) - (10,155)	(13,449) - (13,449)	(16,228) - (16,228)	(14,492) - (14,492)

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Large OTVC (16.0 ft2)-Schedule B (RETROFIT)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
COST EFFECTIVENESS, $/lb						
MC	0.08 - (0.02)	(0.05) - (0.07)	(0.008) - (0.05)	(0.04) - (0.04)	(0.09) - (0.09)	(0.09) - (0.09)
PCE	0.03 - (0.07)	(0.10) - (0.13)	(0.05) - (0.10)	(0.09) - (0.09)	(0.14) - (0.14)	(0.14) - (0.14)
TCE	(0.04) - (0.14)	(0.17) - (0.20)	(0.13) - (0.17)	(0.17) - (0.17)	(0.22) - (0.22)	(0.22) - (0.22)
TCA	(0.06) - (0.16)	(0.19) - (0.22)	(0.15) - (0.19)	(0.19) - (0.19)	(0.24) - (0.24)	(0.24) - (0.24)
CFC-113	(0.56) - (0.66)	(0.69) - (0.72)	(0.64) - (0.69)	(0.68) - (0.68)	(0.73) - (0.73)	(0.73) - (0.73)

Control Strategy 1: Hoist at 11 fpm, Below-freezong FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

In-line (38.0 ft2) - Schedule A (RETROFIT)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Below-freezing FRD	17,700	0	17,700	0	0	17,700
Carbon Adsorber	0	74,900	0	74,900	0	0
Super Heated Vapor	0	0	0	0	3,000	3,000
Sump Cooling	0	0	1,500	1,500	1,500	0
Additional plant space	835	5,568	835	5,568	537	1,372
TOTAL CAPITAL COSTS	18,535	80,468	20,035	81,968	5,037	22,072
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,437	13,092	2,635	13,289	662	2,902
Operating labor	358	1,791	717	2,149	717	717
Supervisory labor		269		269		
Maintenance labor		1,971		1,971		
Maintenance materials		1,971		1,971		
Utilities						
Electricity	363	726	944	1,307	944	726
Steam		563		732		
Cooling Water		1		1		
Miscellaneous operating costs	741	3,219	801	3,279	201	883
TOTAL ANNUALIZED COST, $/yr	3,900	23,604	5,097	24,969	2,525	5,228
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	23,554	23,554	30,620	30,620	32,976	32,976
RECOVERED SOLVENT CREDIT, $/yr						
MC	(6,100)	(6,100)	(7,931)	(7,931)	(8,541)	(8,541)
PCE	(7,302)	(7,302)	(9,492)	(9,492)	(10,223)	(10,223)
TCE	(9,068)	(9,068)	(11,789)	(11,789)	(12,696)	(12,696)
TCA	(9,539)	(9,539)	(12,401)	(12,401)	(13,355)	(13,355)
CFC-113	(21,199)	(21,199)	(27,558)	(27,558)	(29,678)	(29,678)

In-line (38.0 ft2) - Schedule A (RETROFIT)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
NET ANNUALIZED COSTS, \$/yr						
MC	(2,200)	17,503	(2,834)	17,038	(6,016)	(3,312)
PCE	(3,402)	16,302	(4,395)	15,476	(7,698)	(4,994)
TCE	(5,168)	14,535	(6,692)	13,180	(10,171)	(7,467)
TCA	(5,639)	14,064	(7,304)	12,567	(10,830)	(8,127)
CFC-113	(17,299)	2,405	(22,461)	(2,589)	(27,154)	(24,450)
COST EFFECTIVENESS, \$/lb						
MC	(0.09)	0.74	(0.09)	0.56	(0.18)	(0.10)
PCE	(0.14)	0.69	(0.14)	0.51	(0.23)	(0.15)
TCE	(0.22)	0.62	(0.22)	0.43	(0.31)	(0.23)
TCA	(0.24)	0.60	(0.24)	0.41	(0.33)	(0.25)
CFC-113	(0.73)	0.10	(0.73)	(0.08)	(0.82)	(0.74)

Control Strategy 1: Below-freezing FRD
Control Strategy 2: Carbon Adsorption
Control Strategy 3: Below-Freezing FRD; Sump Cooling
Control Strategy 4: Carbon Adsorption; Sump Cooling
Control Strategy 5: Super Heated Vapor; Sump Cooling
Control Strategy 6: Below-freezing FRD; Super Heated Vapor

In-line (38.0 ft2) - Schedule B (RETROFIT)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Below-freezing FRD	17,700	0	17,700	0	0	17,700
Carbon Adsorber	0	74,900	0	74,900	0	0
Super Heated Vapor	0	0	0	0	3,000	3,000
Sump Cooling	0	0	1,500	1,500	1,500	0
Additional plant space	835	5,568	835	5,568	537	1,372
TOTAL CAPITAL COSTS	18,535	80,468	20,035	81,968	5,037	22,072
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,437	13,092	2,635	13,289	662	2,902
Operating labor	1,003	5,016	1,505	5,517	1,505	2,006
Supervisory labor		752		752		
Maintenance labor		5,518		5,518		
Maintenance materials		5,518		5,518		
Utilities						
Electricity	1,017	2,034	1,272	2,289	1,272	2,034
Steam		1,636		1,636		
Cooling Water		3		3		
Miscellaneous operating costs	741	3,219	801	3,279	201	883
TOTAL ANNUALIZED COST, $/yr	5,199	36,788	6,213	37,801	3,641	7,825
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	68,386	68,386	68,386	68,386	96,880	96,880
RECOVERED SOLVENT CREDIT, $/yr						
MC	(17,712)	(17,712)	(17,712)	(17,712)	(25,092)	(25,092)
PCE	(21,200)	(21,200)	(21,200)	(21,200)	(30,033)	(30,033)
TCE	(26,329)	(26,329)	(26,329)	(26,329)	(37,299)	(37,299)
TCA	(27,696)	(27,696)	(27,696)	(27,696)	(39,236)	(39,236)
CFC-113	(61,547)	(61,547)	(61,547)	(61,547)	(87,192)	(87,192)

In-line (38.0 ft2) - Schedule B (RETROFIT)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
NET ANNUALIZED COSTS, $/yr						
MC	(12,513)	19,076	(11,499)	20,089	(21,451)	(17,267)
PCE	(16,001)	15,588	(14,987)	16,601	(26,392)	(22,207)
TCE	(21,130)	10,459	(20,116)	11,473	(33,658)	(29,473)
TCA	(22,498)	9,092	(21,488)	10,105	(35,596)	(31,411)
CFC-113	(56,349)	(24,760)	(55,334)	(23,746)	(83,551)	(79,367)
COST EFFECTIVENESS, $/lb						
MC	(0.18)	0.28	(0.17)	0.29	(0.22)	(0.18)
PCE	(0.23)	0.23	(0.22)	0.24	(0.27)	(0.23)
TCE	(0.31)	0.15	(0.29)	0.17	(0.35)	(0.30)
TCA	(0.33)	0.13	(0.31)	0.15	(0.37)	(0.32)
CFC-113	(0.82)	(0.36)	(0.81)	(0.35)	(0.86)	(0.82)

Control Strategy 1: Below-freezing FRD
Control Strategy 2: Carbon Adsorption
Control Strategy 3: Below-Freezing FRD; Sump Cooling
Control Strategy 4: Carbon Adsorption; Sump Cooling
Control Strategy 5: Super Heated Vapor; Sump Cooling
Control Strategy 6: Below-freezing FRD; Super Heated Vapor

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Small OTVC (4.5 ft2)- Schedule A (NEW)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	1,500	1,500	1,500	2,000	2,000	2,000
Below-freezing FRD	4,500	0	0	4,500	0	0
Bi-parting cover	0	0	7,900	0	0	7,900
1.0 FBR	500	0	0	500	0	0
Enclosed Design	0	3000	0	0	3000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	780	223	223	780	223	223
TOTAL CAPITAL COSTS	7,280	6,223	9,623	7,780	6,723	10,123
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	1,184	1,012	1,566	1,266	1,094	1,647
Operating labor	358	358	0	358	358	0
Utilities						
Electricity	188	200	21	188	200	21
Miscellaneous operating costs	291	249	385	311	269	405
TOTAL ANNUALIZED COST, $/yr	2,022	1,819	1,972	2,123	1,921	2,073
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	1,155 - 1,444	2,022 - 2,310	866 - 1,155	1,444 - 1,733	2,310 - 2,599	1,155 - 1,444
RECOVERED SOLVENT CREDIT, $/yr						
MC	(299) - (374)	(524) - (598)	(224) - (299)	(374) - (449)	(598) - (673)	(299) - (374)
PCE	(358) - (448)	(627) - (716)	(269) - (358)	(448) - (537)	(716) - (806)	(358) - (448)
TCE	(445) - (556)	(778) - (890)	(334) - (445)	(556) - (667)	(890) - (1,001)	(445) - (556)
TCA	(468) - (585)	(819) - (936)	(351) - (468)	(585) - (702)	(936) - (1,053)	(468) - (585)
CFC-113	(1,040) - (1,300)	(1,819) - (2,079)	(780) - (1,040)	(1,300) - (1,560)	(2,079) - (2,339)	(1,040) - (1,300)
NET ANNUALIZED COSTS, $/yr						
MC	1,723 - 1,648	1,296 - 1,221	1,747 - 1,672	1,749 - 1,674	1,322 - 1,248	1,774 - 1,699
PCE	1,664 - 1,574	1,193 - 1,103	1,703 - 1,613	1,676 - 1,586	1,205 - 1,115	1,715 - 1,625
TCE	1,577 - 1,466	1,041 - 930	1,638 - 1,527	1,567 - 1,456	1,031 - 920	1,628 - 1,517
TCA	1,554 - 1,437	1,001 - 884	1,621 - 1,504	1,538 - 1,422	985 - 868	1,606 - 1,488
CFC-113	982 - 722	0 - (260)	1,192 - 932	824 - 564	(159) - (418)	1,083 - 773

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Small OTVC (4.5 ft2)- Schedule A (NEW)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
COST EFFECTIVENESS, $/lb						
MC	1.49 - 1.14	0.64 - 0.53	2.02 - 1.45	1.21 - 0.97	0.57 - 0.48	1.54 - 1.18
PCE	1.44 - 1.09	0.59 - 0.48	1.97 - 1.40	1.16 - 0.92	0.52 - 0.43	1.48 - 1.13
TCE	1.37 - 1.02	0.52 - 0.40	1.89 - 1.32	1.09 - 0.84	0.45 - 0.35	1.41 - 1.05
TCA	1.35 - 1.00	0.50 - 0.38	1.87 - 1.30	1.07 - 0.82	0.43 - 0.33	1.39 - 1.03
CFC-113	0.85 - 0.50	0.00 - (0.11)	1.38 - 0.81	0.57 - 0.33	(0.07) - (0.16)	0.89 - 0.54

Control Strategy 1: Hoist at 11 fpm, Below Freezing FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below Freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

06-Apr-89

Small OTVC (4.5 ft2)- Schedule B (NEW)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	1,500	1,500	1,500	2,000	2,000	2,000
Below-freezing FRD	4,500	0	0	4,500	0	0
Bi-parting cover	0	0	7,900	0	0	7,900
1.0 FBR	500	0	0	500	0	0
Enclosed Design	0	3000	0	0	3000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	780	223	223	780	223	223
TOTAL CAPITAL COSTS	7,280	6,223	9,623	7,780	6,723	10,123
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	1,184	1,012	1,566	1,266	1,094	1,647
Operating labor	717	358	0	717	358	0
Utilities						
Electricity	400	170	127	400	170	127
Miscellaneous operating costs	291	249	385	311	269	405
TOTAL ANNUALIZED COST, $/yr	2,592	1,789	2,078	2,693	1,891	2,179
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	3,468 - 4,855	4,855 - 5,549	3,468 - 4,162	5,549 - 5,549	6,242 - 6,242	5,549 - 5,549
RECOVERED SOLVENT CREDIT, $/yr						
MC	(898) - (1,257)	(1,257) - (1,437)	(898) - (1,078)	(1,437) - (1,437)	(1,617) - (1,617)	(1,437) - (1,437)
PCE	(1,075) - (1,505)	(1,505) - (1,720)	(1,075) - (1,290)	(1,720) - (1,720)	(1,935) - (1,935)	(1,720) - (1,720)
TCE	(1,335) - (1,869)	(1,869) - (2,136)	(1,335) - (1,602)	(2,136) - (2,136)	(2,403) - (2,403)	(2,136) - (2,136)
TCA	(1,405) - (1,966)	(1,966) - (2,247)	(1,405) - (1,686)	(2,247) - (2,247)	(2,528) - (2,528)	(2,247) - (2,247)
CFC-113	(3,121) - (4,370)	(4,370) - (4,994)	(3,121) - (3,745)	(4,994) - (4,994)	(5,618) - (5,618)	(4,994) - (4,994)
NET ANNUALIZED COSTS, $/yr						
MC	1,694 - 1,334	532 - 352	1,180 - 1,000	1,256 - 1,256	274 - 274	742 - 742
PCE	1,517 - 1,087	284 - 69	1,003 - 788	973 - 973	(45) - (45)	459 - 459
TCE	1,257 - 723	(80) - (347)	743 - 475	557 - 557	(513) - (513)	43 - 43
TCA	1,187 - 625	(177) - (458)	673 - 392	446 - 446	(638) - (638)	(68) - (68)
CFC-113	(529) - (1,778)	(2,580) - (3,205)	(1,043) - (1,668)	(2,301) - (2,301)	(3,728) - (3,728)	(2,815) - (2,815)

06-Apr-89

Small OTVC (4.5 ft2)- Schedule B (NEW),

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
COST EFFECTIVENESS, $/lb						
MC	0.49 - 0.27	0.11 - 0.06	0.34 - 0.24	0.23 - 0.23	0.04 - 0.04	0.13 - 0.13
PCE	0.44 - 0.22	0.06 - 0.01	0.29 - 0.19	0.18 - 0.18	(0.01) - (0.01)	0.08 - 0.08
TCE	0.36 - 0.15	(0.02) - (0.06)	0.21 - 0.11	0.10 - 0.10	(0.08) - (0.08)	0.01 - 0.01
TCA	0.34 - 0.13	(0.04) - (0.08)	0.19 - 0.09	0.08 - 0.08	(0.10) - (0.10)	(0.01) - (0.01)
CFC-113	(0.15) - (0.37)	(0.53) - (0.58)	(0.30) - (0.40)	(0.41) - (0.41)	(0.60) - (0.60)	(0.51) - (0.51)

Control Strategy 1: Hoist at 11 fpm, Below Freezing FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below Freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

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Large OTVC (16.0 ft2)- Schedule A (NEW)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	3,000	3,000	3,000	3,500	3,500	3,500
Below-freezing FRD	8,600	0	0	8,600	0	0
Bi-parting cover	0	0	10,200	0	0	10,200
1.0 FBR	600	0	0	600	0	0
Enclosed Design	0	10000	0	0	10000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	1,336	223	223 0	1,3[illegible]	223	223
TOTAL CAPITAL COSTS	13,536	14,723	13,423	14,036	15,223	13,923
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,202	2,395	2,184	2,284	2,477	2,265
Operating labor	358	358	0	358	358	0
Utilities						
Electricity	188	393	36	188	393	36
Miscellaneous operating costs	541	589	537	561	609	548
TOTAL ANNUALIZED COST, $/yr	3,290	3,736	2,757	3,391	3,837	2,850
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	4,107 - 5,134	7,187 - 8,214	3,080 - 4,107	5,134 - 6,160	8,214 - 9,240	4,107 - 5,134
RECOVERED SOLVENT CREDIT, $/yr						
MC	(1,064) - (1,330)	(1,861) - (2,127)	(798) - (1,064)	(1,330) - (1,595)	(2,127) - (2,393)	(1,064) - (1,330)
PCE	(1,273) - (1,592)	(2,228) - (2,546)	(955) - (1,273)	(1,591) - (1,910)	(2,546) - (2,864)	(1,273) - (1,591)
TCE	(1,581) - (1,977)	(2,767) - (3,162)	(1,186) - (1,581)	(1,976) - (2,372)	(3,162) - (3,558)	(1,581) - (1,976)
TCA	(1,663) - (2,079)	(2,911) - (3,327)	(1,247) - (1,663)	(2,079) - (2,495)	(3,327) - (3,742)	(1,663) - (2,079)
CFC-113	(3,696) - (4,621)	(6,468) - (7,392)	(2,772) - (3,696)	(4,620) - (5,544)	(7,392) - (8,316)	(3,696) - (4,620)
NET ANNUALIZED COSTS, $/yr						
MC	2,226 - 1,960	1,875 - 1,609	1,959 - 1,694	2,061 - 1,796	1,710 - 1,444	1,786 - 1,520
PCE	2,017 - 1,698	1,508 - 1,190	1,802 - 1,484	1,800 - 1,481	1,291 - 973	1,576 - 1,258
TCE	1,708 - 1,313	969 - 574	1,571 - 1,176	1,415 - 1,019	675 - 280	1,268 - 873
TCA	1,626 - 1,210	825 - 410	1,510 - 1,094	1,312 - 896	511 - 95	1,186 - 771
CFC-113	(407) - (1,331)	(2,732) - (3,656)	(15) - (939)	(1,229) - (2,153)	(3,555) - (4,479)	(847) - (1,771)

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Large OTVC (16.0 ft2)- Schedule A (NEW)

	Control Strategy 1			Control Strategy 2			Control Strategy 3			Control Strategy 4			Control Strategy 5			Control Strategy 6		
COST EFFECTIVENESS, $/lb																		
MC	0.54	-	0.38	0.26	-	0.20	0.64	-	0.41	0.40	-	0.29	0.21	-	0.16	0.43	-	0.30
PCE	0.49	-	0.33	0.21	-	0.14	0.59	-	0.36	0.35	-	0.24	0.16	-	0.11	0.38	-	0.25
TCE	0.42	-	0.26	0.13	-	0.07	0.51	-	0.29	0.28	-	0.17	0.08	-	0.03	0.31	-	0.17
TCA	0.40	-	0.24	0.11	-	0.05	0.49	-	0.27	0.26	-	0.15	0.06	-	0.01	0.29	-	0.15
CFC-113	(0.10)	-	(0.26)	(0.38)	-	(0.45)	(0.00)	-	(0.23)	(0.24)	-	(0.35)	(0.43)	-	(0.48)	(0.21)	-	(0.34)

Control Strategy 1: Hoist at 11 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

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Large OTVC (16.0 ft2)- Schedule B (NEW)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Hoist	3,000	3,000	3,000	3,500	3,500	3,500
Below-freezing FRD	8,600	0	0	8,600	0	0
Bi-parting cover	0	0	10,200	0	0	10,200
1.0 FBR	600	0	0	600	0	0
Enclosed Design	0	10000	0	0	10000	0
Sump cooling	0	1,500	0	0	1,500	0
Additional plant space	1,336	223	223 0	1,336	223	223
TOTAL CAPITAL COSTS	13,536	14,723	13,423	14,036	15,223	13,923
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,202	2,395	2,184	2,284	2,477	2,265
Operating labor	717	358	0	717	358	0
Utilities						
Electricity	400	303	218	400	303	218
Miscellaneous operating costs	541	589	537	561	609	557
TOTAL ANNUALIZED COST, $/yr	3,860	3,646	2,939	3,961	3,747	3,040
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	12,330 - 17,262	17,262 - 19,728	12,330 - 14,796	19,728 - 19,728	22,194 - 22,194	19,728 - 19,728
RECOVERED SOLVENT CREDIT, $/yr						
MC	(3,193) - (4,471)	(4,471) - (5,110)	(3,193) - (3,832)	(5,110) - (5,110)	(5,748) - (5,748)	(5,110) - (5,110)
PCE	(2,848) - (5,351)	(3,988) - (6,116)	(2,848) - (4,587)	(4,557) - (6,116)	(5,127) - (6,880)	(4,557) - (6,116)
TCE	(4,747) - (6,646)	(6,646) - (7,595)	(4,747) - (5,696)	(7,595) - (7,595)	(8,545) - (8,545)	(7,595) - (7,595)
TCA	(4,994) - (6,991)	(6,991) - (7,990)	(4,994) - (5,992)	(7,990) - (7,990)	(8,989) - (8,989)	(7,990) - (7,990)
CFC-113	(11,097) - (15,536)	(15,536) - (17,755)	(11,097) - (13,316)	(17,755) - (17,755)	(19,975) - (19,975)	(17,755) - (17,755)
NET ANNUALIZED COSTS, $/yr						
MC	666 - (611)	(825) - (1,464)	(255) - (893)	(1,148) - (1,148)	(2,002) - (2,002)	(2,069) - (2,069)
PCE	1,012 - (1,491)	(342) - (2,470)	91 - (1,648)	(596) - (2,155)	(1,380) - (3,134)	(1,517) - (3,076)
TCE	(887) - (2,786)	(3,000) - (3,950)	(1,808) - (2,758)	(3,634) - (3,634)	(4,798) - (4,798)	(4,555) - (4,555)
TCA	(1,134) - (3,131)	(3,345) - (4,344)	(2,055) - (3,054)	(4,029) - (4,029)	(5,242) - (5,242)	(4,950) - (4,950)
CFC-113	(7,237) - (11,676)	(11,890) - (14,110)	(8,158) - (10,378)	(13,794) - (13,794)	(16,228) - (16,228)	(14,715) - (14,715)

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Large OTVC (16.0 ft2)- Schedule B (NEW)

	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
COST EFFECTIVENESS, $/lb						
MC	0.05 - (0.04)	(0.05) - (0.07)	(0.02) - (0.06)	(0.06) - (0.06)	(0.09) - (0.09)	(0.10) - (0.10)
PCE	0.08 - (0.09)	(0.02) - (0.13)	0.01 - (0.11)	(0.08) - (0.11)	(0.06) - (0.14)	(0.08) - (0.16)
TCE	(0.07) - (0.16)	(0.17) - (0.20)	(0.15) - (0.19)	(0.18) - (0.18)	(0.22) - (0.22)	(0.23) - (0.23)
TCA	(0.09) - (0.18)	(0.19) - (0.22)	(0.17) - (0.21)	(0.20) - (0.20)	(0.24) - (0.24)	(0.25) - (0.25)
CFC-113	(0.59) - (0.68)	(0.69) - (0.72)	(0.66) - (0.70)	(0.70) - (0.70)	(0.73) - (0.73)	(0.75) - (0.75)

Control Strategy 1: Hoist at 11 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 2: Hoist at 11 fpm, Enclosed Design, Sump Cooling
Control Strategy 3: Hoist at 11 fpm, Bi-parting Cover
Control Strategy 4: Hoist at 3 fpm, Below-freezing FRD, 1.0 FBR
Control Strategy 5: Hoist at 3 fpm, Enclosed Design, Sump Cooling
Control Strategy 6: Hoist at 3 fpm, Bi-parting Cover

In-line (38.0 ft2) - Schedule A (NEW)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Below-freezing FRD	14,700	0	14,700	0	0	14,700
Carbon Adsorber	0	61,300	0	61,300	0	0
Super Heated Vapor	0	0	0	0	3,000	3,000
Sump Cooling	0	0	1,500	1,500	1,500	0
Additional plant space	835	5,568	835	5,568	537	1,372
TOTAL CAPITAL COSTS	15,535	66,868	17,035	68,368	5,037	19,072
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,043	10,879	2,240	11,077	662	2,508
Operating labor	358	1,791	717	2,149	717	717
Supervisory labor		269		269		
Maintenance labor		1,971		1,971		
Maintenance materials		1,971		1,971		
Utilities						
Electricity	363	726	944	1,307	944	726
Steam		563		732		
Cooling Water		1		1		
Miscellaneous operating costs	621	2,675	681	2,735	201	763
TOTAL ANNUALIZED COST, $/yr	3,386	20,847	4,583	22,212	2,525	4,714
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	23,554	23,554	30,620	30,620	32,976	32,976
RECOVERED SOLVENT CREDIT, $/yr						
MC	(6,100)	(6,100)	(7,931)	(7,931)	(8,541)	(8,541)
PCE	(7,302)	(7,302)	(9,492)	(9,492)	(10,223)	(10,223)
TCE	(9,068)	(9,068)	(11,789)	(11,789)	(12,696)	(12,696)
TCA	(9,539)	(9,539)	(12,401)	(12,401)	(13,355)	(13,355)
CFC-113	(21,199)	(21,199)	(27,558)	(27,558)	(29,678)	(29,678)

In-line (38.0 ft2) - Schedule A (NEW)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
NET ANNUALIZED COSTS, $/yr						
MC	(2,715)	14,746	(3,348)	14,281	(6,016)	(3,827)
PCE	(3,916)	13,545	(4,910)	12,720	(7,698)	(5,509)
TCE	(5,683)	11,779	(7,206)	10,423	(10,171)	(7,982)
TCA	(6,154)	11,307	(7,819)	9,811	(10,830)	(8,641)
CFC-113	(17,813)	(352)	(22,975)	(5,346)	(27,154)	(24,965)
COST EFFECTIVENESS, $/lb						
MC	(0.12)	0.63	(0.11)	0.47	(0.18)	(0.12)
PCE	(0.17)	0.58	(0.16)	0.42	(0.23)	(0.17)
TCE	(0.24)	0.50	(0.24)	0.34	(0.31)	(0.24)
TCA	(0.26)	0.48	(0.26)	0.32	(0.33)	(0.26)
CFC-113	(0.76)	(0.01)	(0.75)	(0.17)	(0.82)	(0.76)

Control Strategy 1: Below-freezing FRD
Control Strategy 2: Carbon Adsorption
Control Strategy 3: Below-Freezing FRD; Sump Cooling
Control Strategy 4: Carbon Adsorption; Sump Cooling
Control Strategy 5: Super Heated Vapor; Sump Cooling
Control Strategy 6: Below-freezing FRD; Super Heated Vapor

In-line (38.0 ft2) - Schedule B (NEW)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
I. CAPITAL COSTS, $						
Below-freezing FRD	14,700	0	14,700	0	0	14,700
Carbon Adsorber	0	61,300	0	61,300	0	0
Super Heated Vapor	0	0	0	0	3,000	3,000
Sump Cooling	0	0	1,500	1,500	1,500	0
Additional plant space	835	5,568	835	5,568	537	1,372
TOTAL CAPITAL COSTS	15,535	66,868	17,035	68,368	5,037	19,072
II. ANNUAL OPERATING COSTS, $/yr						
Annualized total capital costs	2,043	10,879	2,240	11,077	662	2,508
Operating labor	1,003	5,016	1,505	5,517	1,505	2,006
Supervisory labor		752		752		
Maintenance labor		5,518		5,518		
Maintenance materials		5,518		5,518		
Utilities						
Electricity	1,017	2,034	1,272	2,289	1,272	2,034
Steam		1,636		1,636		
Cooling Water		3		3		
Miscellaneous operating costs	621	2,675	681	2,735	201	763
TOTAL ANNUALIZED COST, $/yr	4,684	34,031	5,699	35,044	3,641	7,311
III. COST EFFECTIVENESS						
EMISSION REDUCTION, lb/yr	68,386	68,386	68,386	68,386	96,880	96,880
RECOVERED SOLVENT CREDIT, $/yr						
MC	(17,712)	(17,712)	(17,712)	(17,712)	(25,092)	(25,092)
PCE	(21,200)	(21,200)	(21,200)	(21,200)	(30,033)	(30,033)
TCE	(26,329)	(26,329)	(26,329)	(26,329)	(37,299)	(37,299)
TCA	(27,696)	(27,696)	(27,696)	(27,696)	(39,236)	(39,236)
CFC-113	(61,547)	(61,547)	(61,547)	(61,547)	(87,192)	(87,192)

In-line (38.0 ft2) - Schedule B (NEW)	Control Strategy 1	Control Strategy 2	Control Strategy 3	Control Strategy 4	Control Strategy 5	Control Strategy 6
NET ANNUALIZED COSTS, $/yr						
MC	(13,028)	16,319	(12,013)	17,332	(21,451)	(17,781)
PCE	(16,515)	12,831	(15,501)	13,845	(26,392)	(22,722)
TCE	(21,644)	7,703	(20,630)	8,716	(33,658)	(29,988)
TCA	(23,012)	6,335	(21,998)	7,348	(35,596)	(31,926)
CFC-113	(56,863)	(27,516)	(55,849)	(26,503)	(83,551)	(79,881)
COST EFFECTIVENESS, $/lb						
MC	(0.19)	0.24	(0.18)	0.25	(0.22)	(0.18)
PCE	(0.24)	0.19	(0.23)	0.20	(0.27)	(0.23)
TCE	(0.32)	0.11	(0.30)	0.13	(0.35)	(0.31)
TCA	(0.34)	0.09	(0.32)	0.11	(0.37)	(0.33)
CFC-113	(0.83)	(0.40)	(0.82)	(0.39)	(0.86)	(0.82)

Control Strategy 1: Below-freezing FRD
Control Strategy 2: Carbon Adsorption
Control Strategy 3: Below-Freezing FRD; Sump Cooling
Control Strategy 4: Carbon Adsorption; Sump Cooling
Control Strategy 5: Super Heated Vapor; Sump Cooling
Control Strategy 6: Below-freezing FRD; Super Heated Vapor